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Project Title: Application of Bioreactor Systems to Low-Concentration Perchlorate-Contaminated Water (RFP 2530)

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Application of Bioreactor Systems to Low-Concentration Perchlorate-Contaminated Water

A proposal submitted to AWWARF in Response to RFP 2530
Proposal Dates: 8/16/1998 -8/15/2000

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1.0 ABSTRACT

Perchlorate has recently been detected in several surface waters and ground water wells used to supply drinking water at concentrations above the detection limit (0.4 ppb) to 0.37%. The California Department of Health Services (CDHS), based on EPA work, has established a provisional action level of 18 ppb for drinking water due to perchlorate's interference with iodine in the production of hormones in the thyroid. The presence of perchlorate at these high concentrations in the environment, coupled with a very low drinking water standard, has created a national water contamination crisis in the US potentially affecting 12 million people. Perchlorate is readily biodegradable, and under proper conditions, can be reduced to non-detectable levels by fixed and suspended cultures of microorganisms. Since 1993, the PI has been conducting research on microbes that can respire chlorate or perchlorate: that is, they can use either of these compounds as an electron acceptor in the oxidation of many common substrates such as acetate, simple sugars and amino acids.

It is proposed here to conduct bench scale experiments on three different fixed-film biological treatment processes that should be capable of being scaled up to treat large quantities of drinking water. These treatment systems are: a packed bed (slow sand filter) amended with soluble substrates (acetate, methanol, and ethanol); a hydrogen gas fed four-phase (hydrogen gas, water, biofilm, and support media), unsaturated trickle-type packed column; a membrane-bound biofilm reactor. The hydrogen gas-based systems offer an additional potential advantage of achieving chlorinated aliphatic reduction by hydrogen-oxidizing bacteria under highly reducing conditions. With information gained in this proposal, we will estimate the costs of treating waters using the reactors and feed substrates that successfully remove perchlorate down to drinking water levels (<18 ug/L). Based on the engineering and economic analysis, one of these treatment systems will be selected for further testing in Phase II at the Crafton-Redlands site in Redlands, CA.

reactor types // 4 substrates

This project will involve researchers at Penn State University, the University of Nevada, Las Vegas, the City of Redlands, and Camp, Dresser and McKee (CDM) consulting Engineering. In order to assess the general nature of the findings, and to test the performance of the systems for Phase II work, water samples will be obtained from two sites: the Crafton-Redlands site, and a perchlorate contaminated areas in Nevada (the Nevada Wash area and Lake Mead).

2.0 Table of Contents

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3.0 BACKGROUND

Recent detection of perchlorate in several surface waters and ground water wells used to supply drinking water has created an unforseen water contamination crisis in the Western states, although problems are likely to emerge at other sites where perchlorate is used. It is estimated that as many as 12 million people could be affected by perchlorate contamination of drinking water. In March of 1997, the California Department of Health Services (CDHS) developed a method that reduced the detection limit of perchlorate from 400 ppb to 4 ppb. Based on EPA work, they established a provisional action level of 18 ppb for drinking water. Perchlorate is a health concern due to its interference with iodine in the production of hormones in the thyroid. Subsequent monitoring of 232 groundwater wells by the CDHS indicated perchlorate was in 69 wells (30%) and at concentrations above the action level in 20 wells (9%) (AWWARF 1997). Perchlorate concentrations in surface and groundwater range from detectable (4 ppb) to 0.37%, and endanger extensive use of the Colorado River water in the western states. Samples taken from the Las Vegas Wash, which feeds Lake Mead and then the Colorado River, contained 1,500 to 1,680 ppb (Urbansky 1998). The Los Angeles Metropolitan Water District measured 8 ppb in water at its intake in Lake Mead, and the Southern Nevada Water Authority found 11 ppb in its tap water.

Perchlorate contamination arises from the manufacture and disposal of ammonium perchlorate (AP), a highly energetic compound produced for use as rocket fuel. It is highly soluble and not easily removed from water. It was the consensus of a team of experts that met at a special workshop on perchlorate that "at this time there is no proven removal process available at the low concentrations being found in drinking water" (AWWARF 1997). Typical water treatment technologies such as ion exchange, air stripping, carbon adsorption and advanced oxidation, have had little effect on perchlorate. Aqueous perchlorate solutions are extemely stable; merely lowering the Eh of the water to less than -200 mV does not produce abiotic perchlorate reduction (Bliven 1996).

While perchlorate may not be easy to be chemically treated or physically removed, it is very biodegradable. Since 1993, the PI has been conducting research on microbes that can respire on chlorate (ClO_3^-) or perchlorate (ClO_4^-): that is, they can use either of these compounds as an electron acceptor in the oxidation of many common substrates such as acetate, simple sugars and amino acids. Both chlorate and perchlorate are thermodynamically more oxidized compounds than oxygen and, although it is believed that they do not naturally occur in the environment (in substantial concentrations), both serve as electron acceptors for many different strains of microorganisms (Malmqvist et al. 1991, Hijnen et al. 1995, Korenkov et al. 1976, Wallace et al. 1996). Several strains of chlorate respiring microbes (CRMs) and perchlorate respiring microorganisms (PCMs) are thought to be related to denitrifying organisms, although some chlorate respiring cultures may lose the ability to reduce nitrate when cultivated on chlorate for long periods (Malmqvist et al. 1994).

One of the earliest proposed uses of CRMs was a test to evaluate the concentration of biodegradable organic matter in domestic wastewater by measuring the amount of Cl^- produced from the reduction of ClO_3^- (Bryan and Rohlich 1954, Bryan 1966). CRMs have since been proposed for use in a variety of engineered reactors. For example, chlorate produced during bleaching operations can be removed by CRMs in wastewater treatment lagoons (Malmqvist et al. 1991). Bacteria that have been identified to respire on chlorate have also been shown to reduce bromate (a carcinogen) with the addition of ethanol in batch cultures, and it was proposed to use microbial reduction of bromate (to bromide) for water treatment in water filters (Hijnen et al. 1995). Microbes identified to respire using chlorate and perchlorate include *Vibrio dechloraticans* Cuznesove B-1168 (Korenkov et al. 1976), *Ideonella dechloratans* (Malmqvist et al. 1994), and *Wolinella succinogenes* (Wallace et al. 1996).

Proposed Treatment approach. While information gained in this proposal will be useful in most of the above applications, this proposal is targeted to investigate removal of perchlorate from water, leaving it suitable for drinking water. It is argued here that the most promising systems for microbial respiration of perchlorate are those based on fixed biofilms of microorganisms. A successful treatment system must have the ability to remove the perchlorate, leave very little oxidizable substrate in the water, and produce a water relatively free of bacteria. At many sites where perchlorates have been measured, there is also contamination of the water by chlorinated aliphatics such as TCE. Therefore, the system must either be capapble of degrading this compounds, or, processes must be added (such as air stripping) to remove residual chlorinated compounds.

In order to provide a rationale for the systems proposed in this study, the characteristics of perchlorate- and chlorate-reducing microorganisms, and existing processes using these microbes, are reviewed below. Since many of the attributes of nitrate and chlorate reducing microorganisms are similar, the literature on nitrate reducers is also summarized in order to hypothesize what native attributes might be characteristics of the microbial physiology of (per)chlorate reducing microorganisms. However, there are substantial differences between nitrate reduction and perchlorate reduction that will be noted. The main differences are that: nitrate can be more easily reduced abiotically than perchlorate, for example by zero valent iron; nitrate is reduced to a gas (nitrogen) whereas chlorate is reduced to soluble ion (chloride). Other characteristics of (per)chlorate reducing microbes and denitrifying microbes are reviewed below.

4.0 PROJECT DESCRIPTION

4.1 Phase 1 Research Plan

Objectives. Although perchlorate is biodegradable, the there have been no published studies of treatment technologies for perchlorate contaminated waters that can remove perchlorate to drinking water standards while maintaining water quality sufficient to meet other drinking water standards. The purpose of this project is to explore three reactor designs in terms of their suitability for treating perchlorate contaminated water to produce drinking water. The specific objectives of the proposed research grant will be to:

- Modify a sand filter to treat perchlorate contaminated water to drinking water standards;
- Design and test a gas (hydrogen) phase fixed film bioreactor for efficiency of perchlorate removal;
- Test a membrane-bound hydrogen fed biofilm reactor;

- Make a economic comparison of these reactors if there were to be scaled up to capacities sufficient for large volume of water (millions of gallons per day). Based on what?

To investigate perchlorate degradation for real water sources, we will use contaminated water samples from the Redlands plume and from the Nevada Wash near Las Vegas in Nevada. The Redlands site is specifically indicated in the AWWARF guidelines, and treats water (8.6 MGD) in a full scale faclitity. The Nevada Wash site is extremely important because water from this area feeds into Lake Mead, the water source for the city of Las Vegas, and the Colorado, the water source for millions of people in Arizona and California. Beyond RFP scope

4.1.1 Characteristics of (Per)Chlorate Reducing Microorganisms

Many strains of CRMs share many attributes with denitrifiers, but have some characteristics that are atypical of anaerobic microorganisms. This may be due (in part) to the fact that the theoretical energy yield of chlorate reduction is not only larger than for nitrate, sulfate or iron, but it is also larger than oxygen (Malmqvist et al. 1991). While this situation does not necessarily translate to more ATP production than for these other EAs, measured yields of 0.6 g-cell/g-acetate are larger than those typical of anaerobic processes and at the upper end (0.4 to 0.6) for aerobes (Grady and Lim 1980). Cell doubling times of 6 hr for CRMs have been measured in my laboratory, and these doubling times are among the highest recorded for anaerobes (Logan et al. 1998). good Biochem.

Early Studies on CRMs. Sodium chlorate was first used by Bryan and coworkers (Bryan and Rohlich 1954, Bryan 1966) as an alternative to dissolved oxygen in a BOD test. They found that chlorate concentrations of <1000 mg l^{-1} did not adversely affect calculated biochemical chlorate demands (BCDs) and that overall growth kinetics of chlorate reducers were only slightly less than those observed for aerobic microorganisms. Although chlorate has the potential to form chlorite, a toxic chemical, batch and continuous culture experiments have shown that the only end product of chlorate reduction is chloride ion, a non-toxic end product (Malmqvist et al. 1991). After the earlier studies of Bryan and coworkers, the use of chlorate as an alternate electron acceptor for the degradation of organic matter was largely ignored except for an older patent by Korenkov et al. (1976). More recent studies of microbial growth on chlorate were conducted by Malmqvist and coworkers (Malmqvist et al. 1991, Malmqvist et al. 1994); these studies suggest the researchers thought that they were the first to show that chlorate could sustain microbial growth (they did not mention the earlier work by Bryan and co-workers).

It appears that chlorate respiring microorganisms (CRMs) are widely distributed in the natural environment, although it is not known if chlorate respiration is actually occurring in any of the environments sampled. Bliven (1996) tested different sources for chloride production from chlorate (500 mg/L) in BOD bottles amended with a glucose and glutamic acid solution (final concentration, 300 mg/L). The concentrations of chloride (mg/L) obtained after eight days of incubation by source was: anaerobic digester, 156; pulp and papermill wastewater, 63; primary clarifier effluent, 57; trickling filter effluent, 55; soil sample, 51. van Ginkel et al. (1995) found chlorate reduction by river (Ijssel) samples, anoxic sediments from a ditch, surface soils (from a public garden), and a waste water treatment plant treating primarily domestic sewage. Microbial Microbiology - good reduction of chlorate was supported by several many different organic chemicals, including: carboxylic acids, alcohols (ethanol and propanols), and some amino acids; and inorganic compounds including H_2S and H_2. Oxygen inhibited chlorate reduction, but chlorate was completely converted to chloride in the presence of sulfate, Fe(III) and Mn(IV). Under denitrifying conditions, gas formation but not chloride production was observed implying that nitrate inhibited chlorate respiration (van Ginkel et al. 1995).

Chlorate- and Perchlorate-Respiring Isolates. Differing reports on strain size and morphology, spore formation, and chemicals that serve as reductants make it apparent that the ability to reduce (per)chlorate is not limited to a single bacterial species. It is suspected, although not proven, that isolates capable of perchlorate respiration are also capable of reduction of several other halo-oxygenated compounds such as chlorate. Microbes known to respire both chlorate and perchlorate include: *Vibrio dechloraticans* Cuznesove B-1168 (Korenkov et al. 1976); *Ideonella dechloratans* (Malmqvist et al. 1994); GR-1, a strain identified to belong to the β subgroup of *Proteobacteria* (Rikken et al. 1996); and *Wolinella succinogenes* HAP-1, an obligate anerobe (Wallace et al. 1996). Strains of *Pseudomonas fluorescens* have been found to reduce bromate (Hijnen et al. 1995). One chlorate-respiring isolate, AB-1, identified as most similar to *Comomonas testasteroni* using a Biolog test (as was *I. dechloratans*) was not tested for perchlorate reduction (Bliven 1996) but in all other cases tested, perchlorate reducers also reduced chlorate. All of these chlorate respiring microbes (CRMs) except HAP-1 are facultative anaerobes and are thought to be related to denitrifying organisms; it has been reported, however, that chlorate respiring cultures may lose the ability to reduce nitrate when cultivated on chlorate for long periods (Malmqvist et al. 1994).

Malmqvist and Welander (1992) obtained four chlorate reducing bacterial strains using streak plates and acetate/chlorate agar plates. All four isolates were gram-negative, catalase- and oxidase-positive, motile rods. None of the isolates could use glucose, but Korenkov et al. (1976) indicated growth of their isolate only occurred on glucose in the presence of acetate. They grew aerobically or with nitrate as an electron acceptor. *I. dechloratans* is Gram-negative, motile, rod-shaped (straight or slightly curved, sometimes growing in filaments), and is capable of growth using oxygen or nitrate. It grew on acetate, alanine, asparagine, byutyrate, fructose, glucose, lactate, propionate, pyruvate, and succinate as sole carbon sources, but did not grow on aminobenzoate, phenol and phenylanine. A chlorate respiring isolate was obtained by Bliven (1996), designated AB-1, was a slightly curved rod having a single polar flagellum. It grew aerobically on acetate or anaerobically on acetate and chlorate, but not anaerobically on phenol, benzene, toluene or xylene. Identification of using Biolog microplates indicated a closest similarity to *Comamonas testosteroni* (as was *I. dechloratans*).

The perchlorate-respiring strain, GR-1, isolated by Rikken et al. (1996) was identified as as a Gram-negative, oxidase positive, motile rod. It was isolated from activated sludge on plates containing acetate and sodium perchlorate with incubation under anaerobic conditions. GR-1 grew on acetate, propionate, caprionate, malate, succinate, and lactate, but was unable to grow on glucose, arabinose, mannose, mannitor, N-acetylglucosamine, maltose, gluconate, adipate, and phenyl acetate. GR-1 grew aerobically or on nitrate. It grew on perchlorate in the presence of nitrate, but nitrate decreased measured doubling times from 3 hours to 9 hours. It could also respire on chlorate and

Mn(IV), but not using sulphate, iodate, bromate, chlorite, selenate, or Fe(III).

An obligate anaerobic microorganism capable of perchlorate respiration at concentrations of 7 g/L of perchlorate, first designated as HAP-1, and then later classified as *Wolinella succinogenes* HAP-1, was isolated by Wallace et al. (1996) from an anaerobic sewage enrichment culture using agar plates. It was catalase-negative, with an optimum growth temperature of 40°C (range 20 to 45°C), and grew on H_2 and aspartate, fumarate, and malate, and also on a mixture of H_2 and perchlorate on: pyruvate, succinate, acetate, whey powder, peptone, yeast extract, Brewers yeast, casamino acids, and cottonseed protein. It did not grow on glucose, fructose, galactose, lactose, sucrose, butyrate, citrate, formate, propionate, benzoate, ethanol, methanol, 1-propanol, and starch. Earlier work reported by Attaway and Smith (1993) was conducted using suspended growth reactors that presumably were highly enriched with HAP-1. Aeration was found to inhibit perchlorate reduction, and completely inactived mixed cultures after a 12 hour exposure (Attaway and Smith 1993). The mixed cultures reduced chlorate, nitrate, nitrite, and sulfate. Nitrate or sulfate did not affect reduction; chlorate (10 mM) reduced the rate of reduction, while nitrite and chlorite (10 mM) completely inhibited perchlorate reduction.

Differences and similarities of Denitrifying and (Per)chlorate Reducing Species. Based on the above characteristics of these isolates, there appear to be many common characteristics of these (per)chlorate respiring strains. For all strains (when it was tested), both chlorate and perchlorate could be reduced. Except for *W. succinogenes* (HAP-1), (per)chlorate reduction was partially or completely inhibited by high concentrations of either nitrogen and oxygen, and sulfate could not be used as a terminal electron acceptor. Chlorate-reductase has been isolated from microorganisms that also possess nitrate reductase, implying that chlorate-respiring strains may share many of the attributes of denitrifiers. While it may be that most (per)chlorate strains are facultative anaerobes that are denitrifiers, not all denitrifiers are chlorate reducers. There is also a variable effect of nitrate on (per)chlorate reduction that is interesting. The only exception to the inhibitory effect of nitrate on perchlorate reduction was reported by Attaway and Smith (1993); in their mixed cultures (presumably containing *W. succinogenes* HAP-1), perchlorate was reduced in the presence of nitrate. Although the facultative anaerobe (GR-1) isolated by Rikken et al. (1996) was also able to reduce perchlorate in the presence of nitrate, cell doubling times decreased in the presence of nitrate implying an inhibitory effect of nitrate on perchlorate respiration.

very good background on D.O / NO_3 inhibition

Little is known about the biochemical pathways involved in bacterial utilization of chlorate or perchlorate as an electron acceptor. Although chlorate reductases have been isolated, these enzymes have been obtained from denitrifying strains known to reduce, but not necessarily shown to respire, chlorate. For example, electron transport to oxygen for *Proteus mirabilis* represses formation of nitrate reductase A (NR-A), but in the absence of oxygen and presence of nitrate, NR-A was de-repressed (Oltmann et al. 1976). While the presence of nitrate in turn has been found to repress the expression of chlorate reductase-C (CR-C) in *P. mirabilis*, CR-C is otherwise constitutive even in the presence of oxygen, although it is present at lower per cell activities (DeGroot and Stouthamer 1969). If these enzymes were involved in chlorate respiration, then this suggests that in order for cells to respire using chlorate, both nitrate and oxygen would have to be absent, an observation which is not true for all chlorate respiring strains. In batch cultures, the presence of oxygen may not be detrimental to cell growth for all species examined except HAP-1; because these chlorate reducing isolates have been shown to be facultative aerobes, as long as NO_3^- is absent, dissolved oxygen would be removed by cell growth prior to growth supported by chlorate respiration.

There are important differences in the physiology and biochemistry of denitrifying and perchlorate reducing species. Denitrification does not progress from NO_3^- to N_2 in one step, but rather follows the sequence of: $NO_3 \rightarrow NO_2 \rightarrow NO \rightarrow N_2O \rightarrow N_2$. Thus, overall it is a five-electron transfer process. In contrast, the conversion of chlorine in perchlorate (Cl^{+7}) to chloride (Cl^-) requires the overall transfer of eight electrons-- and it can be accomplished completely by one bacterium without the detection of toxic intermediates in solution (such as chlorite). The reason for this in at least one strain was determined by Van Ginkel et al. (1996). They were able to isolate a novel enzyme (chlorite dismutase, from strain GR-1) capable of conversion of chlorite (ClO_2^-) to oxygen. This implies a sequence of perchlorate reduction of $ClO_4^- \rightarrow\rightarrow ClO_2^- \rightarrow O_2 + Cl^-$, where the multiple arrows indicate the potential for intermediates such as ClO_3^-. [Recall that GR-1 was a facultative anaerobe capable of reducing a variety of compounds including chlorate, nitrate, and Mn(IV)]. Oxygen produced from chlorite was not found to accumulate in solution, and therefore oxygen was probably used by GR-1 as an electron acceptor. It is not yet known if chlorite dismutase is present in other strains of chlorate and perchlorate microorganisms. GR-1 is the only facultative anaerobce that can continue to reduce chlorate in the presence of nitrate, suggesting that other strains may not necessarily contain chlorite dismutase.

answer for part of objective 2

Perchlorate reduction is significantly different from nitrate in that perchlorate is extremely stable in water. Many inorganic chemists use perchlorate under highly reducing conditions in order to maintain ionic strengths while studying the reduction of more easily reduced compounds (Espenson 1997). Perchlorate should, from a thermodynamic perspective, react with many metal complexes but in fact it is stable with almost all complexes except methyl rhenium dioxide suspensions at low pH (where it has very high reaction kinetics) (Espenson 1997). In contrast, nitrate is quite reactive. For example, nitrate was found to be completely reduced by granular metallic iron and hydrogen with a palladium catalyst (with nitrite as an intermediate) within 14 minutes (Siantar et al. 1996). However, both chlorate and perchlorate are stable in water in the presence of zero-valent iron (unpublished data).

Influence of co-contaminants on Treatment Efficiency. We have previously investigated the potential of using (per)chlorate respiring microbes for degradation of persistent chemicals such as benzene, toluene, and xylene. We were unable to obtain cultures that could oxidize these chemicals while reducing perchlorate. However, we did find that phenol could serve as the sole substrate for growth of mixed cultures under chlorate reducing conditions (Logan et al. 1998). Both anaerobic and aerobic pathways are known for phenol degradation. Under denitrifying conditions, phosphate is added to phenol and then carboxylation of phenylphosphate occurs by phenol carboxylase to produce 4-hydroxybenzoate. Since CRMs may have had access to low concentrations of oxygen in chemostat work it is possible that microaerophilic processes may be may be necessary for pollutant degradation. Mono and dioxygenases are important in a number of aromatic compound degradation pathways. Phenol degradation under aerobic conditions by *Pseudomonas putida* occurs by oxygen insertion into the ring leading to ring cleavage and mineralization of phenol. The work by van Ginkel et al. (1996) demonstrating that oxygen is produced by chlorite dismutase, suggests that oxygen could be available for oxygenases to use for ring cleavage.

There is great potential for the degradation of chlorinated aliphatics in mixed cultures under hydrogen oxidizing conditions for two reasons. First, a bacterium has been isolated that is capable of reductively dechlorinating tetrachloroethylene (PCE) to ethylene when grown with H_2 (Maymo-Gatell et al. 1997). It may be possible to bioaugment perchlorate-respiring cultures and biofilms with these microbes in order to facilitate reductive dechlorination of some chemicals. Second, many other chemicals can be reduced under methanogenic conditions (Ballapragada et al. 1997). Although we will not intentionally try to develop a methanogenic consortium, some growth of methanogens is likely in hydrogen fed reactors. The growth of these cells might be sufficient to degrade chlorinated chemicals in the water.

Review of Application and Success of Engineered (Per)Chlorate BioReactors. Reactors are needed for two different goals: wastewater treatment, and drinking water treatment. Microbiological degradation of chlorate and perchlorate to low levels has been achieved so far only in engineered bioreactors suitable for wastewater treatment. The distinction between water and wastewater reactors is simply that for water treatment, there must be no toxic chemicals and little organic matter remaining in solution. For wastewater treatment, microbes and organic matter can remain in the water if it is to be discharged to a receiving water body or a POTW. Examples of these wastewater reactors, that include both small and large, continuous reactors, include: chlorate (produced during bleaching operations) removal by CRMs in wastewater treatment lagoons (Malmqvist et al. 1991); bromate removal by the addition of ethanol for water treatment in water filters (Hijnen et al. 1995); perchlorate removal from rocket propellent wash waters (Attaway and Smith 1993, Wallace et al. 1996); sand columns in the presence of excess acetate (Logan and Kim 1998). The development of biological reactors for water treatment requires new design strategies. To date, there are no large scale biological drinking water treatment systems in the United States. Thus, there is no established basis of design information to use to develop (per)chlorate drinking water treatment systems.

Here is the rub!

In order to specify design characteristics of a new biological treatment process, in terms of reactor detention time or loading rate, kinetic constants and growth yields for mixed or pure cultures would need be known or pilot or full-scale operation data would need to be available. Important kinetic constants include: μ_m, the maximum growth rate, K_s the half saturation constant), and b an endogenous decay coefficient. In order to microbiologically reduce (per)chlorate, an oxidizable substrate will need to be added to a bioreactor. Any remaining substrate will need to be removed to limit subsequent biological growth in the water distribution system. Due to cell maintenance and energy requirements, there is a minimum achievable substrate concentration that is a function of the reactor configuration and microbial kinetic constants. For example, the minimum substrate concentration achievable in a completely mixed, constant flow suspended growth bioreactor is: $S_{\min} = b\, K_s/\mu_m - b$, where Y is the yield of cell biomass produced per substrate consumed (Logan 1998b). In order to calculate this minimum substrate concentration, we need to know values of these constants.

actually Monod!

To determine growth rate constants for chlorate-respiring mixed cultures, Logan and co-workers (Patnaik 1996, Bliven 1996, Olsen 1997, Logan et al. 1998) conducted laboratory-scale chemostat experiments using nitrogen-air purged reactors fed different substrates: acetate, glucose-glutamic acid, and phenol. Reactors were small capacity (0.5 - 1 L working volume) run at room temperature with no recycle. Chlorate was added in excess in order to measure kinetic parameters for growth on the oxidizable substrates. Maximum growth rates using acetate, glucose-glutamic acid, and phenol were 0.56, 0.12 and 0.040 h^{-1}, with cell yields of 0.12, 0.41, and 0.12 g-cell/g-substrate, respectively (Logan et al. 1998). These results indicate that growth rates of CRMs are quite high, and indicate that CRMs might be able to out compete other anaerobic microorganisms for oxidizable substrates in water treatment bioreactors. However, some minimum concentration of substrate will remain in solution. Assuming an endogenous decay coefficient of b=0.005 d^{-1}, acetate would only be reduced to S_{min}=0.26 mg/L based on the kinetic constants given above for acetate.

There have been a few other published reports on reactors suitable for treating (per)chorate, but much of the information is incomplete with respect to engineering design information such as microbial growth constants, cell yields, and reactor configuration details. For example, Malmqvist and Welander (1992) reported that fixed film reactors could be used to eliminate chlorate from paper mill wastewaters, but the type of media packing and other reactor configuration details were not provided (Malmqvist and Welander 1992). In laboratory tests, chlorate (50 mg/L) in a kraft mill wastewater (COD=1600 mg/L) was 100% removed (no detection limit noted) at detention times larger than 0.6 hr under conditions of 37°C and at a wastewater pH=7. In pilot tests, in a 20 m^3 reactor operating at a pH range of 6.2-7, a temperature range of 36 to 38°C, and influent chlorate concentrations of 40 to 75 mg/L, removals were complete at a detention time of 12.8 h, with removals of >90% at detention times of 1.6 h.

Malmqvist et al. (1991) conducted laboratory-scale chemostat experiments at 37°C at pH=7, using a 0.36 L working volume in a 0.4 L reactor, and no recycle. The reactor (but not the feed) was sparged with nitrogen to maintain anoxic conditions, and only one detention time of 25 hours was examined. Chlorate removal at concentrations of 83 to 1250 mg/L (1-15 mM) was complete with stoichiometric conversion to chloride. Cell yields were high, ranging from 1.9 to 3.8 g-VSS per g-equivalent electrons.

Researchers at the Tyndall Air Force Base have developed a suspended growth reactor to remove perchlorate from high concentrations (3000 mg/L) down to relatively lower concentrations (<0.5 mg/l). Some information on their system is contained in two publications (Attaway and Smith 1993, Wallace et al. 1996) while other information is available through internet postings (www.brooks.af.mil, and www.afcesa.af.mil). Their skid-mounted system consisted of two reactors, a 1300 L anaerobic reactor and a 2700 L aerobic reactor, complete with automatic pH control, clarifier and feed and product holding tanks. Their anaerobic reactor used primarily cultures of *Wollinella succinogenes* HAP-1 with Brewer's yeast as a nutrient source. In a pilot test that began in May of 1995, and ran for >600 hours, they examined the effect of reactor detention times of 8-36 hours on perchlorate reduction; perchlorate was reduced to <0.5 mg/L even at the lowest detention times. Although this system was successful at treating perchlorate-contaminated waste water, it is unlikely that this system could be used to treat drinking water to acceptable levels (<18 ug/L) due to high concentrations of organic matter used in the system.

It has also been reported that Aerojet has developed an anoxic fluidized bed methanol-fed reactor capable of treating perchlorate down to 100 μg/L (AWWARF 1997), but details of this process are not available because of the proprietary nature of this process. While it is not known whether this process would be suitable for treatment of water to drinking water standards, in general fluidized bed reactors are quite expensive and thus such a process might not be economical for large scale water treatment.

Fixed bed systems hold great promise for water treatment. It has recently been shown that perchlorate can be removed to below detectable levels in fixed bed sand filters inoculated with perchlorate-degrading enriched cultures. Logan and Kim (1998) developed a perchlorate degrading biofilm in 14.2-cm long sand columns by injecting enriched cultures into the column. After incubating them overnight (30°C), the column was switched to continuous flow and fed an artificial groundwater amended with acetate, trace minerals and nutrients (ammonia and phosphorus), and 20 mg/L of perchlorate. Oxygen was not removed from the feed water, but instead was allowed to be removed within the column by the microbial consortia, resulting in anoxic conditions. Perchlorate concentrations in the column effluent were below detectable levels (<4 μg/L) at loading rates of <0.11 gpm/ft^2. Higher loading rates (>0.12 gpm/ft^2) resulted in perchlorate breakthrough producing high effluent concentrations (>150 μg/L) that rapidly increased with hydraulic loading.

A critical factor in the design of reactors for water treatment will be the choice of oxidizable substrate added to the reactor. Acetate has been used extensively in laboratory work, but acetate may not to be cost effective for larger systems. Likely alternative candidates as oxidizable substrates include: ethanol, methanol, and hydrogen gas. Of these, hydrogen is particularly appealing and is the subject of a recent patent application (Logan 1998c). Chlorate respiring microorganisms are known to oxidize hydrogen. This gas is sparingly soluble, and therefore would not be likely to persist in water in appreciable quantities. Methanol and ethanol may also prove useful, but cost efficiency of these and other substrates has not be evaluated at this time. For the use of any substrate to be evaluated, bench and pilot studies will be necessary to determine optimum feed rates, reactor detention times, and so forth. In addition, such systems may require the inclusion of other unit processes. For example, water polishing by conventional filtration or further treatment in additional biological reactors to remove any residual substrate in the water may be necessary. For systems containing treating low concentrations of perchlorate in water (<100 μg/L), it may also be necessary to include a system for regenerating perchlorate degrading capacity of the biofilm by taking the system off line and feeding the reactor high concentrations of chlorate and oxidizable substrate (Logan 1998b). The fact that (per)chlorate respiration proceeds in the absence of substrate in the source water (i.e. the microbes can use stored substrates) may make it possible to develop reactors based solely on endogenous decay. Laboratory and pilot scale testing will be necessary to determine which of these approaches will ultimately prove to be the most stable and economical. interesting

It seems that Logan has already a good idea of the biology of ClO_4 reduction
Moving to reactor types

4.2 Proposed Experiments

It is proposed here to develop anaerobic, fixed film reactors capable of removing perchlorate down to concentrations necessary to meet drinking water standards (<18 ppb). Three biological fixed film systems are proposed: a sand filter of the type normally used in drinking water systems; a gas-phase (hydrogen gas) reactor; and a membrane-bound biofilm reactor. The requirement of <18 ppb of perchlorate for these reactors is substantially different than that used in past research by others to treat waste waters (to <1000 ppb). In order to design a water treatment reactor to achieve these low perchlorate concentrations, we would conduct bench scale studies necessary to evaluate different substrates suitable for drinking water supplies (hydrogen gas, ethanol, methanol); these would be compared to rates obtained using acetate as the sole energy source. Acetate has been shown to serve as an electron donor in studies demonstrating the removal of perchlorate to <18 ppb in batch and column experiments (Logan and Kim 1998). We would then conduct more detailed studies to identify optimal substrate (feed) concentrations and reactor detention times. It is expected that the system would need to be a one to three compartment reactor system as described below. A patent on the first two reactor designs, and the concept of fueling these reactors using hydrogen gas, has been filed by the PI and Penn State University (see attachment for a copy of the patent disclosure).

4.2.1 Reactor Types and Configuration

Given that large volumes of non-sterile water will pass through the reactor, it will be impossible to maintain pure culture conditions in the bioreactors; therefore, the reactors must be designed to operate using mixed cultures. While it may not necessary to operate the reactor as a pure culture, it still may be helpful to inoculate it with either an adapted culture or a known strain of cells in order to rapidly develop a perchlorate respiring population in the reactor. Such an acclimated mixed culture is easily obtained via standard enrichment techniques using wastewater or soil samples (Bliven 1996, Olsen 1997, Logan et al. 1998). For reasons of public acceptability, we would obtain an enrichment culture from the Nevada Wash in Las Vegas (where soils have long been exposed to perchlorate), or use isolates from such a culture. We have already obtained soil samples from this area and are in the process of characterizing these bacteria. (Funding for current work on obtaining and studying (per)chlorate reducing isolates is from in-house funds and a grant from NSF on chlorate respiring microorganisms). These microbial strains and communities would be used in reactors described below. It should also be noted that in hydrogen gas reactors, it may also be desirable to bioaugment the system with a strain of microbe capable of dehalogenating chloratinated aliphatic molecules (see below, section 4.4.7). In all cases, however, it is recognized that the reactors will need to operate as mixed cultures. Strategies to maintain a dominant perchlorate respiring culture, such as media mixing and culture regeneration, will be examined as described below.

4.2.2 Sand Column Fixed-Film Bioreactor

This perchlorate biofilm reactor will be an anaerobic biofilm packed bed reactor used specifically to grow perchlorate-respiring bacteria and treat water (surface water and ground water) to remove perchlorate to the ppb range or lower. The reactor will consist of a laboratory-scale sand column of the type typically used for water treatment following coagulation/ sedimentation tanks,

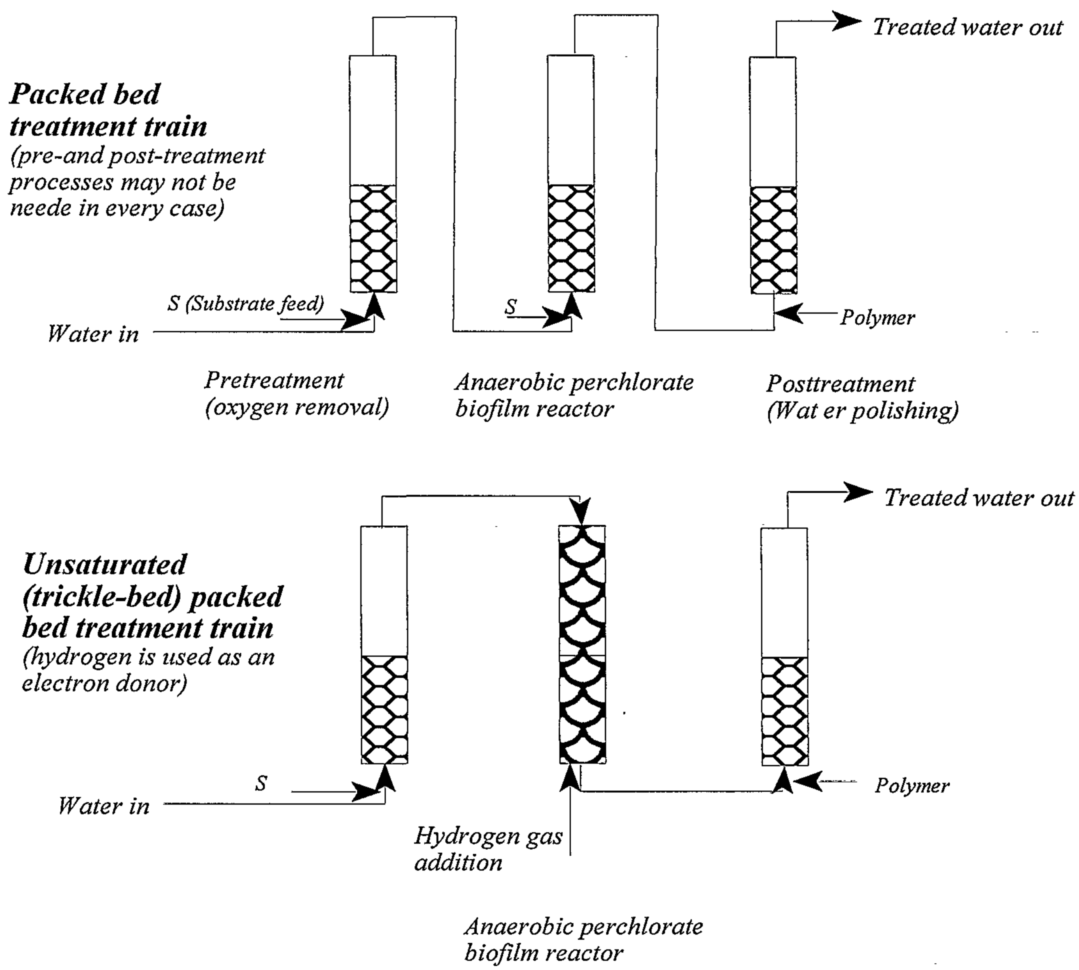

Figure 1. *(A) Process train for treating perchlorate contaminated water. The pre-and post-treatment trains may not be needed in all cases. Pretreatment functions to consume all oxygen for the anaerobic perchlorate biofilm reactor, while posttreatment is provided to remove any sloughed biofilm and to provide for biological polishing of any remaining growth substrate (S) in the water sample. (B) Here, the biofilm reactor is shown to contain a gas phase of hydrogen that serves as the electron donor in the biological process.*

but modified to allow for the introduction of chemical substrates to serve as an electron donor (Figure 1). The filter will be a dual media filter operated in either up-flow or down-flow mode, with most of the filter composed of sand with the bottom media consisting of gravel. The reactor would be inoculated, and operated in recycle mode until a biofilm had been developed as indicated by a loss of perchlorate in the system. The system would be fluidized (i.e. backwashed), but it would be done very gently and for the sole purpose of homogenizing the column media. The reactor could then be operated again in plug flow mode again with fresh feed water containing one of the supplemental carbon sources and perchlorate-amended artificial groundwater.

There are two important components to this reactor: the ability to regenerate the biofilm; and the ability to fluidize and mix the filter media. Because of the low perchlorate concentrations present in many drinking water sources, there might not be sufficient perchlorate in the water to support a perchlorate respiring biofilm in competition with other anaerobes (such as methanogens) even though the cell yields and growth rates of these other anaerobic communities are so low compared to perchlorate respiring strains. Thus, we anticipate needing to periodically *regenerate a thick perchlorate respiring biofilm* by periodically infusing the column with high concentrations of chlorate (not perchlorate) and substrate. The biofilm in this reactor would therefore be regenerated by: temporarily halting the flow of contaminated water through the reactor; recycling water containing relatively high concentrations of electron donor and electron acceptor (chlorate, at 10-1000mg/L levels) to that bacteria so that they may into a thick biofilm; the reactor would then be rinsed with clean water, and placed back into service. Thus, the bacteria in the biofilm would scavenge perchlorate while in endogenous decay. The biofilm would be regenerated as often as necessary, but it should certainly be on a less frequent time scale than needed for a water treatment filter for ordinary backwashing.

Second, the reactor will be able to be periodically fluidized for two reasons. One, it may be necessary to periodically redistribute bacteria that preferentially will grow near the column effluent to the whole column. Two, it may be necessary to periodically dislodge old biofilms (or other material that may accumulate on the media packing) to prevent the sand bed from clogging. The need to only periodically fluidize the bed, versus continuously fluidize the bed (as proposed by others) means that operation costs are substantially reduced for normal operation compared to a fluidized bed.

Contaminated water from the regeneration cycle (possibly containing high concentrations of chlorate or electron donor) would be held for subsequent treatment. Excess chlorate would rapidly be removed in the presence of excess electron donor. Excess electron acceptor could be removed through ordinary anaerobic treatment processes such as methanogens. In our laboratory, we find that water in batch culture can be disposed of after a day or so. In a water treatment plant, we expect such water could be added back into the flow entering the perchlorate reactor.

As described above, perchlorate removal from 20 mg/L to 18 µg/L in sand columns has already been proven in our laboratory (Logan and Kim 1998) at loading rates of <0.11 gpm/ft^2. Higher loading rates (>0.12 gpm/ft^2) resulted in perchlorate breakthrough producing high effluent concentrations (>150 µg/L) that rapidly increased with hydraulic loading. However, substrate (acetate) concentrations remained high in the column effluent, and the system would need to be optimized in order to minimize effluent substrate concentrations. These loading rates are also quite low (relative to water treatment filters). It is hoped that operation strategies related to biomass redistribution and regeneration will allow these loading rates to be increased making the process more economically efficient.

4.2.3 Hydrogen-fed Gas Phase Unsaturated Fixed-Film Perchlorate Reactor.

It is undesirable to operate a water treatment reactor under conditions that leave high concentrations of oxidizable substrate in the water as this could lead to increased bacterial growth in water distribution lines. In order to avoid any problems with excess substrate (such as methanol, ethanol or acetate) remaining in the reactor, we propose to design an unsaturated media filter using hydrogen as an electron donor. CRMs have been found to be able to use hydrogen (van Ginkel et al. 1995) and to fix carbon using carbon dioxide. Because PRMs are also CRMs, we believe it should be possible to remove perchlorate using hydrogen as a feed. Hydrogen is sparingly soluble, and thus would not accumulate in water leaving the plant, it is non-toxic, and can easily be generated on any site electrolytically using only water. While the hydrogen would be consumed by the microorganisms, oxygen could either be captured and re-sold, or used as an oxygen source for post-treatment polishing of the effluent in a downstream reactor.

The hydrogen reactor consists of packing (likely plastic support media) to provide a high surface area to volume ratio, and also a high void fraction to avoid clogging and therefore for this case, not to necessitate backwashing (Figure 1). Hydrogen gas (either fed from a containerized source or created on site electrolytically or by another means) would be added into the reactor gas phase, but oxygen would be excluded from the gas phase. Oxygen can easily be consumed with a platinum catalyst in the gas phase, although this would only need to be used during start up or during times when the reactor is exposed to air (or turned off for long periods of time). We assume that any oxygen in the water entering the reactor would be quickly consumed by the biofilm. The water would trickle down through the reactor, so that the microbes growing on the column packing could use the hydrogen gas as an electron donor (food source) and use the perchlorate as an electron acceptor (for respiration) accomplishing perchlorate removal. Thus, this reactor is essentially a type of trickling filter reactor commonly used for wastewater treatment and gas transport into the wetted film can be described by adapting gas transport models for fixed film systems (Logan et al. 1993)

The design of such gas phase reactors for water treatment has been tried in the past. For example, it has been proposed to treat waters contaminated with volatile organic compounds, such as TCE, using methanotrophs (methane oxidizing bacteria). We would use the results of those studies in considering additional details of our reactor design. The main limitations of these methanotrophic reactors, versus those proposed here, is that toxic intermediates are produced during TCE breakdown but such toxic intermediates do not accumulate during perchlorate degradation.

4.2.4 Membrane-Biofilm Reactor

A disadvantage of the above systems is that bacteria used to degrade the perchlorate will come directly into contact with the water being treated. It is possible to design a biological reactor using a semi-permeable membrane so that the bioreactor is kept separate from the water sample (Sakakibara et al. 1994, Metcleaf and Schroeder 1995). Therefore, it is proposed to build and test a combined reactor consisting of a diffusion reactor (DR) and a biological reactor (BR), separated by a microporous membrane (Figure 1). (This part of the research project would be conducted as a subcontract to Dr. Jaci Batista at UNLV). In this membrane-bioreactor setup, a perchlorate contaminated stream is allowed to flow into the DR chamber, and a concentration gradient is set up across the microporous membrane by consumption of perchlorate in the BR chamber. Chloride can diffuse back into the DR chamber preventing the buildup of ions in the BR chamber.

There is no need to maintain a pressure difference across the membrane because the transport of ions is solely based on diffusion, and therefore the resulting process is not energy-intensive. The

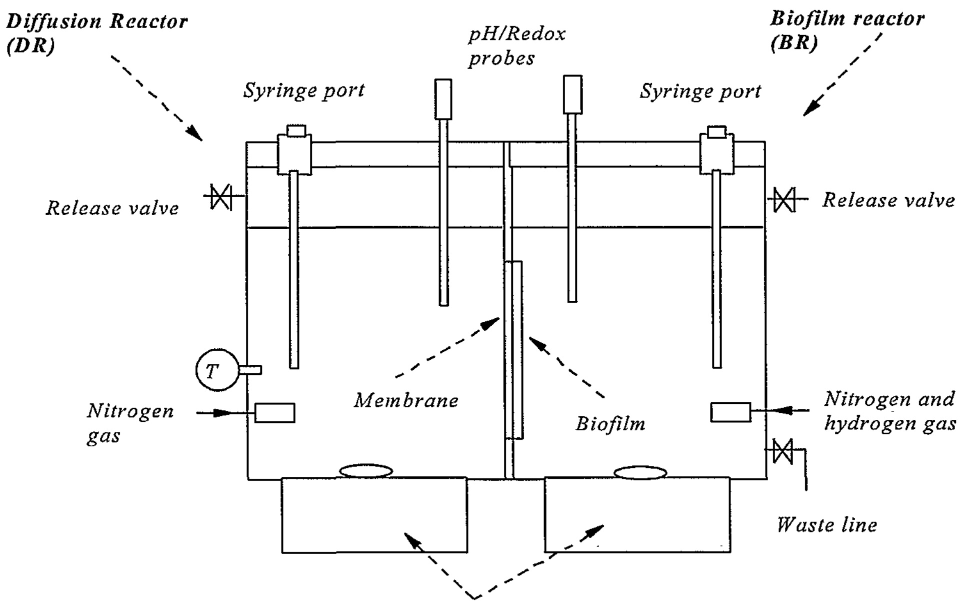

Figure 2: Membrane Reactor

pore size of the microporous membrane will be chosen so that perchlorate can diffuse into the BR chamber while the back transport of microbial cells and macromolecules into the DR chamber is minimized. A hydrogen oxidizing biofilm will be developed to reduce perchlorate. Because hydrogen is maintained on one side of the biofilm, and the perchlorate diffuses from the other side, the loss of hydrogen can be minimized by adjusting the hydrogen atmosphere in the BR chamber in order to meet the perchlorate flux across the membrane.

Mass transport and microbial kinetics can be separately determined. The diffusion rate across the membranes will be computed by filling both tanks with perchlorate-free water and then spiking the DR tank with the perchlorate and measuring contaminant concentration in both chambers as a function of time. A range of perchlorate concentrations from 0.1 to 100 mg/L will be tested. Initially, samples of the BR tank every 15 minutes but this is subject to changes based on initial perchlorate concentration in the DR tank. Microbial kinetics will be calculated as indicated above for other biofilm reactors.

4.3 Factors Related to Assessing Reactor Performance

Water Samples and Influent Perchlorate Concentrations. An artificial ground water (AGW) would be used in most studies. This water would be constructed using ultrapure/low ionic strength water (~0.01 mM, produced from a Millipore Academic Q water treatment system) and amended with trace metals and ionic species to mimic the water at the Redlands site in conductivity, major ionic species (i.e. sulfate, nitrate, phosphate), pH, dissolved organic carbon. Further along in the study, when reactor designs are optimized, we will conduct experiments at the University of Nevada, Las Vegas, using water from Lake Mead (spiked with perchlorate) and contaminated water samples from groundwater wells that have been turned off in the area due to perchlorate contamination to verify the general applicability of our degradation kinetics. As a common starting point in our studies, we would use water containing perchlorate at 1 mg/L, with an experimental range of 10 to 1000 ppb, and set as a goal to achieve a reduction to non-detectable levels (<5 ppb).

Carbon Source and Nutrient Requirements. As indicated above, the energy and carbon sources that would be examined in this study are: hydrogen gas and CO_2; methanol, ethanol, and acetate. Additional nutrients are necessary for cells to make new biomass, to provide essential nutrients, and to identify critical trace metals. Nutrient requirements would consist of nitrogen and phosphorus, provided in a ratio to the amount of carbon used (or fixed) as 100:20:1, with the nitrogen added as ammonia and the phosphorus as phosphoric acid. We would measure N and P in the reactor effluents in order to optimize nutrient additions. The need for trace metals is more difficult to determine. Important metals are likely Mo (for denitrifiers), Fe and Cu. It is likely that the water will contain sufficient quantities of these metals. However, as a part of an NSF project, we are investigating the nutritional requirements of (per)chlorate respiring microorganisms. As a result of that work, we should be able to identify if trace metals will need to be added (preferably in the bioreactor regeneration step and not into the feed water).

Reaction Mechanisms, Intermediates, and Analytical Methods. It is hypothesized that no intermediates will accumulate in solution during the reduction of perchlorate to chloride. However, potential intermediates are: chlorate and chlorite. The presence of chlorite is of particular concern as it is quite toxic. These chemicals will be measured in reactor effluents using ion chromatography as described below (section 4.4.9).

Determination of Reaction Rates. There are two types of reaction rates of concern here: intrinsic kinetics, and overall reactor kinetics. Uptake kinetics are usually described in term of Michaelis-Menton kinetics, where the rate of chemical disappearance is

$$R = \frac{dS}{dt} = -\frac{X}{Y_{X/S}}\frac{\mu_{\max} S}{(K_s + S)} \qquad \textbf{(1)}$$

where S is the substrate concentration, $Y_{X/S}$ is a yield coefficient based on cells produced per substrate consumed, X (mg L^{-1}) the cell mass concentration, μ_{max} is the maximum (saturation) uptake rate constant and K_s is half-saturation constant or the substrate concentration that produces an uptake rate of $\mu_{max}/2$. The cell yield is calcualted in batch growth experiments based on cells produced per substrate consumed. To determine the kinetic constants, we will conduct uptake studies while holding X constant and allowing S to vary. The constants can then be calculated from double reciprocal plots using standard techniques (Logan 1998b).

Reactor reaction rates will be determined differently depending on the reactor configuration. The overall non-steady mass balance for a fixed-bed biofilm reactor (Logan 1998b) is:

$$\theta\frac{\partial S}{\partial t} = -u_x\frac{\partial S}{\partial x} + E_L\frac{\partial^2 S}{\partial x^2} - a_b J_b - \frac{\theta\,\mu_{\max} X S}{Y_{X/S}(K_s + S)} \qquad \textbf{(2)}$$

where the term on the left hand side indicates accumulation, and the right hand terms represent advection, hydrodynamic dispersion, chemical flux into the biofilm, and uptake by suspended cells. The constants are: θ=porosity, u_x the fluid velocity, E_L the dispersion coefficient (measured using a bromide tracer), and J_b the flux into the biofilm. If the packing is assumed to consist of spherical particles, the specific surface area, a_b, can be calculated from the media packing size using a_b=6(1-

$\theta)/d_c$, where θ is the bed porosity and d_c the diameter of the packing media. The flux can be calculated from perchlorate measurements made along the length of flow in the packed bed reactor. The expression of the flux in terms of kinetic parameters is described elsewhere (and is too lengthy to be reproduced here) but allows comparison to reactor performance compared to that predicted based on the intrinsic constants measured above. This is important as a comparison to actual performance with that predicted by a completely homogeneous biofilm that reduces perchlorate, allows calculation of the performance of the bed versus that possible. That is, we can determine the extent that the reactor performance is reduced due to consumption of substrate by non-perchlorate respiring cells in the biofilm.

In order to assess the performance of the hydrogen gas reactor, existing mechanistic models developed by the PI for trickling filters (e.g. Logan et al. 1987a, b; Logan et al. 1990; Logan 1993) can be modified, and, these models compared to an empirical description of the rate of perchlorate removal in unsaturated packed beds. Empirical models of chemical removal, such as the modified Velz equation, are based on first-order rates resulting in exponentially decreases of chemical concentrations with reactor height (Logan 1998b).

Operating Conditions. The bioreactor systems will be routinely operated using water designed to mimic the water quality of the Redlands site in terms of pH, ionic strength and ionic composition. Once performance is determined with the AGW, then key performance conditions will be re-examined using water from the Redlands and Nevada Wash sites. This water will be shipped to the respectively laboratories in 55-gal drums; the quality of this water will be compared with identical water samples shipped overnight in coolers to ensure minimal change in water quality during transport. Comparison of samples will be made in terms of conductivity, major ionic species (i.e. sulfate, nitrate, phosphate), pH, dissolved organic carbon, and perchlorate concentration. Reactors will usually be run at room temperature (20°C). In the latter experimental phase we will examine the effect of temperature by placing the complete reactor in a temperature controlled room (set at groundwater temperatures at the Redlands site).

Influence of Co-Contaminants. Nitrate is expected to be a common co-contaminant in perchlorate contaminated waters, and nitrate has been reported to reduce and even inhibit (per)chlorate respiration by batch cultures. It is expected that the primary effect of nitrate in the water on process performance would be to increase the requirement for oxidizable substrate. Initial work will be conducted here with the fixed film reactors using samples not containing any nitrate. As successful operating conditions are identified we will move to introduce nitrate into the water to examine the effect on perchlorate reduction and the amount of oxidizable substrate necessary to support denitrification by the biofilms.

As noted above, there are pure strains known to degrade even relatively recalcitrant molecules such as tetrachloroethylene (Maymo-Gatell et al. 1997). In the second year of study, we will introduce co-contaminants (such as TCE and PCE) at 10 mg/L levels in order to study the effect of the potential degradation of these chemicals in the highly reducing environment achieved during perchlorate reduction (~-300 mV; Bliven, 1996). Based on these results, we will then work on more complex matricies similar to those found at sites in California.

Effect of Dissolved Oxygen. Many perchlorate respiring isolates are facultative anaerobes capable of cell respiration using oxygen. Column tests conducted in our laboratory so far suggest that oxygen is well removed microbiologically in the column, allowing perchlorate reduction to proceed; that is, we do not need to remove oxygen prior to biological treatment of the water. We will monitor the concentration of oxygen, the redox environment (using standard DO microprobes and ORP probes) to verify the removal of oxygen in the reactors. Unless we find that oxygen persists for a long travel time in the reactor, we will not explore the pretreatment of the water to remove oxygen. The presence of oxygen could be most important for the hydrogen reactor, as the gas phase will be well distributed in the column (see section 4.4.10).

Characterization of Effluent Concentrations. Perchlorate will be measured at concentrations above 1 mg/L using a perchlorate specific probe (Orion Research Inc.). Interferences by other anions are known, and include for example at the 10 mg/L concentration: I^-, 25 mg/L; ClO_3^-, 166 mg/L; NO_3^-, 310 mg/L; SO_4^{-2}, 19,200 mg/L. In order to assure that other anions do not interfere with the values obtained using the perchlorate probe, we will verify probe results using our ion chromatograph method. Perchlorate can be measured down to concentrations of 4 ug/L using a procedure developed by Dionex, using an AS-11 column, with a 100 mM NaOH solution, sparged with helium gas, as eluent (Wirt et al. 1998). For concentrations up to 1000 μg/L, a 2 ml injection is used; calibration standards of 5, 12, 25, 100 and 1000 ug/L are used. At higher concentrations, a 25 μl injection is used with calibration standards of 0.5, 1, 10 and 20 mg/L. Concentrations larger than 20 mg/L are diluted manually with ultrapure water. Chlorate, chloride and acetate are similarly measured, on the IC, except the necessary eluent is 0.3 mM $NaHCO_3$+0.9 mM Na_2CO_3 and only the 25 μl injection loop is used. Metals will be measured using atomic absorption spectroscopy using Standard Methods. We will sample oxygen and redox environment using standard microprobles and ORP probes.

Identification of Pre- and Post-Treatment Requirements. Each of the perchlorate bioreactors to be investigated may need to be part of a series of reactors, with each of the reactors optimized for a different objective. For example, we may find that the hydrogen gas reactor is not sufficiently stable due to the presence of oxygen in water in the feed (anoxic conditions are necessary to promote perchlorate reduction). Thus, pretreatment may be necessary by using a small bioreactor (packed bed) optimized to consume a minimal amount of substrate under aerobic conditions, accomplishing the removal of the initial dissolved oxygen in the water. A post-treatment reactor may need to be added following the perchlorate biofilm reactor to remove any remaining electron acceptor in this post treatment process. This could be an anaerobic reactor where carbon dioxide serves as an electron acceptor, or an aerobic reactor where oxygen can be used as an electron acceptor. If the second reactor is aerobic, it may serve a dual function of removing volatile co-contaminants such as TCE. It is hoped that such add on reactors are not necessary, as they will increase the cost of the overall treatment system. Experiments will be ordered such that it will first be tested if such reactors are not necessary.

4.4 Estimating Costs and Scale-Up Issues

Costs and scale up issues will be conducted by CDM. To evaluate the costs of larger systems, design engineers will begin by establishing a process schematic that identifies all elements and processes necessary to reduce perchlorate to drinking water standards for each viable process option. The process schematic will be used to develop design criteria for the key unit processes, such as the biological reactor and a possible post-treatment (filtration) process. The conceptual schematic and design criteria serve as a basis for developing estimating curves for both capital and operating costs. The curves will provide an estimated cost for various flow rates of the entire treatment process. It is key that the assumptions and included costs are listed and described for each curve.

Scale-up issues related to each process will be identified and discussed as part of the Phase 1 work. The focus will be on key factors necessary to move from laboratory-scale pumping and monitoring systems to larger pilot- or full-scale systems. Process detention times and hydraulic inefficiencies need to be identified to determine if the laboratory results can be practically used in the drinking water or remediation industry. Other factors, such as reactor materials needed for the process and well-head system compatibility, will be addressed.

4.5 Phase 2 Research Plan

CDM would take the lead on the project for Phase 2 operations consisting of the design and operation of a pilot-scale system at the City of Redlands site, with the Pis on this project (Logan and Batista) serving as consultants. CDM and The City of Redlands have previously worked together on projects, and the City is willing to cooperate in the testing of pilot scale systems. The purpose of the pilot scale system will be to verify and refine the process effectiveness, conceptual design criteria and costs, and scale-up factors. Primary tasks included for Phase 2 include protocol development and approval by the PAC, pilot system design and fabrication, testing, reporting of results, and report preparation.

CDM is a company with sufficient experience in the design of both water treatment systems and groundwater remediation systems to successfully carry the results of Phase 1 to the pilot (Phase 2), and finally, to full scale implementation. The protocol will set the variables and establish controls that will be tested along with sample collection and analytical techniques. The design, and subsequent fabrication, of the pilot-scale system will use the experience of CDM staff to assure that each process simulates a full-scale installation. The progress reports for Phase 2 will describe the specific results from the ongoing tests. Finally, the report will discuss key operational and design factors that should be considered for a full-scale system with enough details for use by other utilities that have perchlorate in their drinking water supply.

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van Ginkel, G.C., G.B. Rikken, A.G.M. Kroon, and S.W.M. Kengen. 1996. Purification and characterization of chlorite dismutase: a nove oxygen generating enzyme. *Arch. Microbiol.* 166:321-326.

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5.0 Applications Potential

This project outlines methods to treat water contaminated with perchlorate at low concentrations. The benefits of such a treatment technology are obvious, given that over 12 million people may be impacted by the presence of perchlorate in drinking water. The proposed project outlines a technology suitable for treatment of water directly from a source, but the bioreactors developed in this research project may have additional applications. If a physical method (such as ion exchange, GAC or a membrane process) is found to economically remove the perchlorate from drinking water sources, a wastewater containing perchlorate would still be generated and need to be treated. The biological processes described in this proposal would all be applicable to treatment of the more concentrated perchlorate solutions, and in fact, could generate water that could be added upstream back into the water system. Thus, even if biological treatment is not selected as a primary treatment scheme for perchlorate removal, biological treatment of waste streams is still possible using the proposed bioreactors.

To summarize, it is expected that Phase I of this research effort should produce the following:

- Results that demonstrate that perchlorate can easily be removed to below drinking water standards (<18 ug/L), and likely reduce perchlorate to non-detectable levels (<5 ug/L), in biological fixed-film reactors:
- A comparison of the efficiencies of three bioreactor systems for removing perchlorate;
- An examination of the effects of different electron donors on perchlorate removal and reactor stability;
- Provide a recommendation for optimum reactor conditions to maximize reactor efficiency;
- Produce an economic analysis that compares overall cost efficiency of the treatment processes. The work proposed should be sufficient to reduce perchlorate.

As a result of Phase 1 of this project, we would have the necessary design information to implement a pilot scale test at the Crafton-Redlands Plume in the Redlands, California. The Phase 2 work would be directed by CDM, with the PIs on the current project serving as consultants.

6.0 Quality Assurance Narrative Statement

This project will involve primarily two areas that will require strict quality assurance: sample collection and tracking; analytical measurements. The activities performed on this project and other details are outlined in specific sections below.

Activities to be performed. The specific activities related to this project have already been described in this proposal. The main dependent variable in this project is perchlorate concentrations. We will be able to achieve for probe measurements a precision of ±10% of sample concentration or ±2 mg/L, whichever is the greater number, and for ion chromatograph ±5% of sample concentration or ±1 μg/L, whichever is the greater number, based on duplicate measurements. Accuracy will be demonstrated by calibration standards on each experimental run, or for runs spanning several days, on each day, using an ion chromatograph when concentrations are <1 mg/L. At higher concentrations, we will use a perchlorate ion selective probe. Accuracy of the probe will be verified using two to three calibration standards. Representativeness and completeness of our protocol will be shown by running all column studies in duplicate.

Study Design. This study is primarily a laboratory project. For laboratory tests, we will create an artificial ground water based on samples from the Nevada wash. In later studies, we will use water from sites in California and Nevada. The artificial groundwater made up will be based on the major ionic species in the water.

Sample Handling. All water samples will be shipped in 55-gallon drums to our laboratory, and stored in a refrigerator at 4°C. Smaller samples will be shipped using overnight mail, and preserved with dry ice to keep them cool during shipping. Water samples will be held in polycarbonate carboys. Perchlorate is non-volatile and non-adsorbing, and therefore we do not expect any degradation of samples during shipping. Soil samples used to develop a perchlorate degrading consortium will be placed in 5 gallon carboys. Cooling these samples is essential to preserve the microbial community in the samples. Samples will be marked to indicate: person taking samples, date, time, contents (water), location sample obtained, conditions (temperature), and date received.

Methods of Sample Analysis. Water samples from the Redlands and Nevada sites will be analyzed for major ionic species, metals, and total organic carbon by a commercial water laboratory certified for such analysis. Soils used in columns will be analyzed for size distribution and organic carbon. Soil grain sizes will be measured by sieving, followed by image analysis (Galai Image analysis system) of particle sizes to determine the particle size distribution within size classes. Organic carbon will be measured through combustion by a commercial laboratory.

Perchlorate concentrations above 1 mg/L can be analyzed using an ion specific probe (Orion), and verified by ion chromatography (Dionex DX-100). For verification of perchlorate at these concentrations, and analysis of samples at concentrations of 5 ug/L (detection limit) to 1 mg/L, we plan to use a new perchlorate IC method developed by Dionex (Wirt et al. 1998).

Calibration procedures. Ion specific probes will be calibrated using three calibration standards at concentrations of 1, 20, and 100 mg/L. Higher concentrations will be diluted if necessary. Our ion chromatograph (IC) has an autosampler. Each day the autosampler is run, we will run calibration standards containing four to five known concentrations depending on the sample concentration range.

In order to check our procedures with those of an approved water quality laboratory, we would send samples to Bernard Bubnis, President, Novatek, for comparison of water analysis on perchlorate, chlorate, nitrate and major anions. We would perform this comparison with each new water sample and at least quarterly.

Data Reduction and Reporting. Results of all analyses will be kept in hand written laboratory notebooks. Samples will be reported as averages of multiple analyses. Steady state reactor operation will be verified by measuring reactor outflow over times larger than 3 reactor detention times.

Intended use of data. These data will be used to show that perchlorate can be removed biologically from water. Experimental variables will be changed only one at a time. Controls are included in each experimental phase to ensure that results are attributable to the intended variable.

Quantitative Procedures to evaluate project success. The maximum contaminant level of our research is to remove perchlorate to <18 ug/L. With uncertainty in precision and accuracy, we therefore must show that removal is complete to 16.2 mg/L based on a single reactor, but should be <15.3 allowing for variations between reactors. We believe that operationally, a more useful concentration may be <10 ug/l may be more useful to design engineers, but as a MCL goal, we hope to achieve below detectable levels of < 5 ug/L.

7.0 Project Schedule

This project will be conducted over a tow year period to begin in August of 1998. The responsibilities of the PI and the co-PI are summarized in Table 1 according to tasks and year. Each year is divided into three sections in order to be compatible with reports every four months to AWWARF. In the first year, water samples would be collected and analyzed, and the reactors built and tested using base conditions of an artificial groundwater. In the second year, the reactors would be optimized for performance by varying input loads (such as concentration of applied substrate,

Table 1. Project schedule according to research task and year.

Year	Research Tasks by PI/Location	
	PI: Bruce Logan/Penn State	co-PI: Jaci Batista
Year 1 (1998-1999)	Build reactors, develop perchlorate degrading consortium. Obtain water samples and characterize water.	Same tasks as outlined for PSU work, except all tests done using membrane reactor.
	Perform first set of laboratory experiments (sand and hydrogen-gas reactors) to identify reactor performance under base conditions.	
	Test different feed substrates for perchlorate removal efficiency.	
Year 2 (1999-2000)	Vary inlet concentrations of perchlorate, applied substrate concentrations.	
	Optimize reactor conditions and perform economic comparisons of design.	
	Write up final report on reactor performance and comparisons.	

nutrients, etc.). The second year's work would end with an economic analysis and a final report submitted to AWWARF. Research at UNLV would proceed along the same time line, except that all work would be done on the membrane bioreactor. CDM would be responsible for working with the City of Redlands in obtaining water samples, running conventional water treatment analyses, and in the second year conducting an economic evaluation of costs of the treatment systems and projected costs for scale up of the systems.

There would be several added benefits to conducting this project at Penn State University. First, the National Science Foundation has funded a project in the PI's laboratory on chlorate respiring microorganisms. The NSF project is directed at understanding the microbial physiology of these organisms. Funding of this AWWARF project would provide a complimentary research effort, but one that is directed at a more applied outcome. There is a lot unknown about the microorganisms capable of chlorate and perchlorate respiration, and such knowledge is helpful in designing reactors for chemical treatment. It is envisioned that this AWWARF project, if funded, would proceed more rapidly and be more successful as a result of discoveries made during the NSF project investigation. Second, there is a separate proposal by Dr. Fred Cannon, also at Penn State, under the AWWARF program. If both proposals were funded, this would further a synergistic effect on perchlorate research.

8.0 Statement of Qualifications

The Principal Investigator for this project, Dr. Bruce Logan, is the Kappe Professor of Environmental Engineering at Penn State University. Dr. Logan's areas of expertise are in environmental transport processes, hazardous waste treatment, and wastewater treatment processes, and he is the author or co-author of over 70 refereed publications in technical journals and a textbook on environmental transport of chemicals. He received has received several awards and various fellowships and scholarships as a part of his graduate studies. In 1993 he was a Fulbright Scholar at the University of Constance (Germany), he is a member of Phi Lambda Upsilon, a Chemical Honor Society, and President of the Association of Environmental Engineering Professors (AEEP). He worked for two years as an Environmental Engineer for Stone and Webster in Boston, MA, and was on the faculty at the University of Arizona in the departments of Chemical and Environmental Engineering, and Civil Engineering and Engineering Mechanics (as Assistant through Full Professor) from 1986 to 1997.

Dr. Logan has been working since 1993 with microbes that can respire on chlorate or perchlorate as an electron acceptor. This work has been funded through two grants from the National Science Foundation. The current grant is directed at isolating microbes that can respire on chlorate and simultaneously degrade toxic pollutants. He has also worked extensively in two areas realted to the current proposal: the design of fixed-film biological reactors, and cell attachment/ biocolloid transport. He is an expert in the design of fixed film bioreactors, such as trickling filters, used in wastewater treatment. He has developed computer models to predict trickling filter performance based on mass transport through the liquid film and biofilm kinetics. These models are used for reactor design as described in the Water Environment Federations Manual of Practice (MOP 8). Bacterial transport in aquifers may be crucial for certain bioremediation projects. Subsurface bioremediation using selected and genetically engineered microorganisms is dependent on our ability to transport these microbes into the porous media. Without certain precautions and treatment, microbes will usually travel only centimeters in the soil before being removed by filtration processes. Through chemical modifications of bacterial surfaces and the suspending solution it is possible to enhance bacterial transport over distances of 10s of meters. As a part of this research he is investigating factors that control bacterial attachment to surfaces and other microorganisms. Recent work concerns the effects of air sparging and NAPLs in groundwater on bacterial transport in both saturated and unsaturated soils.

CDM. Camp Dresser & McKee Inc. (CDM), founded in 1947 and headquartered in Cambridge, MA, has over 2,400 professionals located in over 90 offices worldwide. The staff of environmental consulting and engineering professionals includes professional engineers registered in all 50 states and more than two dozen foreign countries; registered architects and geologists; and certified construction specifiers, cost engineers, and environmental managers. CDM's Southern California offices include Irvine, Long Beach, Ontario and Carlsbad. CDM's knowledge and proximity to the site will expedite interactions with the City of Redlands during Phase 1 testing, and will be particularly important during Phase 2 testing at the Redlands site.

CDM is an industry leader in the development, treatment, and delivery of safe drinking water.

Table 2. Groundwater remediation technologies employed by CDM.		
■ Bioremediation	■ Groundwater extraction	■ "Lasagna" technique -- electrokinetic transport
■ Intrinsic bioremediation	■ Pump-and-Treat	■ Landfarming/land treatment
■ Biopiles	■ Isolation/containment	■ Incineration
■ Bioventing	■ *In situ* soil treatment	■ Chemical fixation
■ Soil vapor extraction	■ Activated carbon adsorption	■ Zero valence iron wall
■ Air sparging/biosparging	■ Low-temperature thermal treatment	■ Horizontal well installation
■ Air stripping	■ Steam stripping	■ Ozone-hydrogen peroxide oxidation
■ Biological treatment barrier walls		

CDM has provided expert engineering in every aspect of water quality technology - investigation, development, facility design, and operations. The company focuses on a three-barrier approach to water quality that addresses protection of the water source, effective water treatment and disinfection, and reliable delivery of safe drinking water. They have recommended and designed advanced treatment to restore water supplies contaminated by chemical spills, and have designed supply and treatment systems of up to 1,000 million gallons per day in all sectors of the world. Overall, CDM has designed more than 130 new or expanded water treatment facilities ranging in capacity from 100 gallons per day to 1 billion gallons per day. In the past 10 years, CDM staff has conducted dozens of water treatment pilot studies that have lead to the design and implementation of new or expanded treatment facilities. The staff has also designed and fabricated custom pilot systems used for all aspects of water treatment.

CDM is highly experienced in the design of remedial systems for soils and groundwater. CDM has performed remedial investigations and environmental site assessments for over 20 years. They have conducted hundreds of remedial investigations on projects with local, state, and federal oversight, including Superfund remediation investigations/feasibility studies and RCRA facility investigations. Their designs include new and innovative technologies, which in combination with traditional methods, provide optimal reliability and cost-effectiveness. Design services can include treatability testing; conceptual and preliminary designs; detailed drawings and specifications; and cost estimating.

CDM had completed over 300 remedial planning projects. One of the most critical aspects of the remedial planning process is a thorough evaluation of remedial technologies applicable to site specific conditions. CDM has conducted numerous technology evaluations to support feasibility studies for hazardous materials remediation. These evaluations have addressed a variety of contaminated media, including soil and groundwater, in different settings, for numerous organic and inorganic contaminants. Project objectives include technical (e.g., volume reduction, toxicity reduction, immobilization), financial (e.g., balancing short-term capital costs versus long-term operation and maintenance [O&M] costs), or logistical (e.g., access constraints with current or future operators/landowners at the sites) considerations.

CDM has evaluated and/or used to remediate soil and groundwater include, but are not limited to, those technogies shown in Table 2. In particular, they have extensive experience with the bioremediation of chlorinated hydrocarbons, including: induced biodegradation of chlorinated solvents (e.g., TCE and PCE. CDM; intrinsic (biological) remediation, including its use for sites where chlorinated solvents in the soil/groundwater system were shown to be undergoing natural dechlorination. At several sites, CDM is currently applying *in situ* bioremediation technologies to remediation chlorinated solvents. For example, at the Gilbert-Mosley site in Wichita, Kansas, CDM developed and piloted genetically selected, site-specific microbes to treat chlorinated solvents in groundwater under unique hydrogeological conditions. This pioneering work has the distinction of being the first such project in the United States. Such experience could be important in future work on soil aquifer remediation. CDM was recently selected by U.S. EPA to review the Air Force's technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater.

CDM Experience with City of Redlands. CDM has previous experience at working with the City of Redlands. They recently completed the construction of an award winning wellhead treatment facility for the City of Redlands. The facility removes the contaminant trichloroethylene (TCE) from groundwater, allowing the city to reclaim a "lost" water supply of 3 million gallons per day and augment efforts to clean up the groundwater basin. The City of Redlands depends on groundwater from 31 wells for almost half of its potable water needs. They retained CDM to evaluate design and construct a wellhead treatment system for the Rees Well. The facility went on line in July 1991 and was designed and constructed on a fast-track schedule to meet peak summer water demands during the fifth year of the California drought. For this innovative wellhead treatment facility, American City & County magazine awarded a 1991 Award of Merit to Redlands, California.

8.1 Location of the proposed Research Project and Available Facilities

This research project will be conducted at primarily at Penn State, under the direction of Dr. Bruce Logan. Laboratory studies, as described in the previous section, for the sand and hydrogen gas reactor would be performed in the Kappe Laboratories (see facilities below). The co-PI at UNLV, Dr. Jaci Batista, will direct research related to the membrane-biofilm reactor. Facilities available in her laboratory are also described below.

Facilities available at Penn State. The Kappe Laboratories are located in the Sackett Building on the main campus, and in the Wastewater Treatment Laboratories, and cover an area of approximately 14,000 ft^2. The laboratories are supervised by a full time Laboratory Manager (Mr. Gerry Zimmerman). Major equipment in the Kappe Environmental Engineering laboratories include:

- Ion chromatograph: Dionex DX-100 with autosampler for detection of chlorate, perchlorate, and other anions;
- Gas chromatographs (4): Varian models 3400 (2); Hewlett Packard model 5870 GC; SRI 8610.
- Carbon analyzers with autosamplers (2): Shimadzu TOC 5000A; Dohrmann TOC analyzer.
- Particle counters (3): Coulter Counter Multisizer 2 (resistance-type) with computer interface; Coulter PCA 2; Galai CIS-100 laser particle counter with computer interface system.

- High- pressure liquid chromatographs (2): Hewlett Packard 1100 LC and a Waters M-501.
- UV spectrophotometers (2): Shimadzu UV 1601 and Perkin Elmer.
- Atomic absorption spectrophotometer (Perkin-Elmer Model 3030B).
- Anaerobic chamber: Coy 7080 with heated chamter and oxygen:nitrogen detector.
- Micrometrics 2000 Accelerated Surface Area and Porosimetry Units (2) with Density functional theory pore analysis software; Thermogravimetric analyzers (2): Cahn TG-131, TG-121; Accelerating rate calorimeter (CSI); Thermal reactivation furnace (Applied Test Systems 3210).
- Microscopes: Zeiss Axiophot microscope with image analysis and photometric detection; Olympus BH-2 with image analysis and epifluorescence capabilities.
- Various other equipment including: Microbics Toxicity Analyzers (2): Model 2055, Model 500; Walk-in environmental chambers (4); Anaerobic and aerobic respirometer systems; Laminar flow hood for sterile microbiological work: Biosafety Class II; vertical flow; Fisher Scientific; Fermentors (2) capable of operating in batch or chemostat mode: Centrifuges (3): Sorvall 5C high speed refrigerated; benchtop refrigerated centrifuge (Eppendorf 5403) with various rotors for medium to small sample volume; microcentrifuge (Eppendorf 5415) for small (1.5 ml) samples; Ozone Analyzer (Dasibi Environmental Corp 1008-HC); UV lamp advanced oxidant generation system; Membrane filtration systems (2): Reverse osmosis unit (Desal); ceramic cross flow membrane apparatus (MSC Liquid Filtration Corp.); various ovens; laboratory shakers, filtration boxes, ultrafiltration cells, rotoevaporator (Buchi Rotavapor, R-114); Millipore Academic-Q ultrapure water system with RO pretreatment; and balances.

Facilities at UNLV. The co-PI's research laboratory at the University of Nevada Las Vegas (UNLV) occupies 1,200 sq ft. The facilities includes: an Ion-chromatograph (Dionex-DX 100 with conductivity and electrochemical detectors) for measuring perchlorate, fume hoods, electronic balances, pH meters, ovens, optical microscope, glassware and major analytical equipment such as an atomic adsorption spectrometer (Perkin-Elmer 4100 Zeeman), gas chromatographs (Hewlett Packard 5890 series), total organic carbon analyzer (ASTRO 2001), UV-visible spectrophotometer, desktop spectrophotometer, autoclave, IBM-PC for data collection, Hach COD digestor, turbidity meter, conductivity meter, dissolved oxygen meter, and a jar test device for flocculation studies.

8.2 Resumes of Key Personnel

BRUCE ERNEST LOGAN

Kappe Professor of Environmental Engineering, Dept. Of Civil and Environmental Engineering,
The Pennsylvania State University, University Park, PA 16802-1479
Phone: 814-863-7908, Fax: 814-863-7304, Email: blogan@psu.edu

EDUCATION

1986 Ph.D. in Environmental Engineering, University of California, Berkeley
1980 M.S. in Environmental Engineering, Rensselaer Polytechnic Institute
1979 B.S. in Chemical Engineering, Rensselaer Polytechnic Institute

EXPERIENCE

1997 - present Kappe Professor, Department of Civil and Environmental Engineering, The Pennylvania State University, University Park, PA.

1986 - 1997 Associate Professor (1992-1997), Assistant Professor (1986-1992), Dept. of Chemical and Environmental Engineering; Investigator, Center for Toxicology (1993-1997), University of Arizona, Tucson, AZ.

1980 - 1982 Hazardous Waste Specialist and Waste Treatment Engineer, Stone and Webster Engineering Corporation, Boston, MA.

JOURNAL PUBLICATIONS- Most related to Proposed Project (partial list)

Logan, B.E., A.R. Bliven, S.R. Olsen, and R. Patnaik. 1998. Growth Kinetics of Mixed Cultures under Chlorate-Reducing Conditions. *J. Env. Engrg.*, In press.

Logan, B.E. 1998. A review of chlorate and perchlorate respiring microorganisms. Bioremediation J. Submitted.

Camesano, T.A. and B.E. Logan. 1998. Influence of fluid velocity and cell concentration on the transport of motile and non-motile bacteria in porous media. *Environ. Sci. Technol.*, In press.

Martin, M.J., B.E. Logan, W.P. Johnson, D.J. Jewett, and R.G. Arnold. 1996. Scaling bacterial filtration rates in different sized porous media. *J. Environ. Engng.*, 122(5):407-415.

Aiken, B.S. and B.E. Logan. 1996. Degradation of pentachlorophenol by the white rot fungus *Phanerochaete chrysosporium* grown in ammonium lignosulphonate media. *Biodegradation,* 7(3):175-182.

Alleman, B.C., B.E. Logan, G.L. Amy and R.L. Gilbertson. 1995. Degradation of pentachlorophenol by white rot fungi in rotating tube bioreactors. *Wat. Res.* 29(1):61-67.

Logan, B.E. 1993. Oxygen transfer in trickling filters. *J. Environ. Engin.* 119(6):1059-1076.

Logan, B.E., S.W. Hermanowicz and D.S. Parker. 1987. A fundamental model for trickling filter process design. *J. Water Pollut. Control Fed.*, 59(12):1029-1042.

JOURNAL PUBLICATIONS- OTHER

Logan, B.E. 1998. Environmental Transport Processes. Wiley, New York. (Accepted for publication)

Confer, D.R., and B.E. Logan. 1998. Location of protein and polysaccharide hydrolytic activity in suspended and biofilm wastewater cultures. *Wat. Res.*, 32(1):31-38.

Confer, D.R. and B.E. Logan. 1997. Molecular Weight Distribution of Hydrolysis Products during Biodegradation of Model Macromolecules in Suspended and Biofilm Cultures II: Dextran and Dextrin. *Wat. Res.*, 31(9):2137-2145.

Logan, B.E. and R. Patnaik. 1997. A gas chromatographic based headspace biochemical oxygen demand test. *Water Env. Res.*, 69(2):206-214.

Li, X. and B.E. Logan. 1997. Collision Frequencies of Fractal Aggregates with Small Particles by Differential Sedimentation. *Environ. Sci. Technol.*, 31(4):1229-1236.

Logan, B.E., D.G. Jewett, R.G. Arnold, E. Bouwer and C.R. O'Melia. 1995. Clarification of clean-bed filtration models. *J. Environ. Eng.* 121(12): 869-873.

Gross, M.J. and B.E. Logan. 1995. Influence of different chemical treatments on transport of *Alcaligenes paradoxus* in porous media. *Appl. Environ. Microbiol.*, 61(5):1750-1756.

Logan, B.E. and J.R. Kilps. 1995. Fractal dimensions of aggregates formed in different fluid mechanical environments. *Water Res.* 29(2):443-453.

Haldane, G.M., and B.E. Logan. 1994. Molecular size distributions of a macromolecular polysaccharide (dextran) during its biodegradation in batch and continuous cultures. *Wat. Res.* 28(9):1873-1878.

Logan, B.E., B.C. Alleman, G.L. Amy and R.L. Gilbertson 1994. Adsorption and removal of pentachlorophenol by white rot fungi in batch cultures. *Wat. Res.* 28(7):1533-1538.

PROFESSIONAL REGISTRATIONS AND HONORS

President (1997-1998), Vice President (1996-1997) and Board Member (1995-1999) of the Association of Environmental Engineering Professors (AEEP).

Parsons Engineering Science/AEEP Outstanding Doctoral Dissertation Award (1997): Advisor to Dr. Xiaoyan Li

USANC Founders Award (1995) for best paper in Water Research by a US author (Haldane and Logan, 1994)

Fulbright Scholar- 1993 (University of Constance, Germany)

University of California Regents Fellowship 1982 - 1983

Rensselaer Polytechnic Institute Scholarship 1975 - 1979

New York State Regents Scholarship 1975 - 1979

Lewis J. Coonley Award in Chemical Engineering (R.P.I. 1979)

Phi Lambda Upsilon - Chemical Honor Society

PROFESSIONAL MEMBERSHIPS

American Association for the Advancement of Science (AAAS)
American Chemical Society (ACS)
American Society of Civil Engineers (ASCE)
American Society for Limnology and Oceanography (ASLO)
American Society for Microbiology (ASM)
Association of Environmental Engineering Professors (AEEP)
International Association on Water Quality (IAWQ)
Water Environment Federation (WEF)

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EDUCATION

1995 Ph.D. Environmental Engineering, The Pennsylvania State University, University Park, PA. GPA 3.6/4.0. Advisors: Dr. James C. Young and Dr. Kwadwo A. Osseo-Asare

1990 M.S. Environmental Engineering, Montana College of Mineral Science and Technology, Butte, Montana, December 1990.

1987 B.S. Mining Engineering, Federal University of Ouro Preto, Ouro Preto, Minas Gerais, Brazil. Rank: 3/83.

PROFESSIONAL POSITIONS AND EXPERIENCE

1997-present Assistant Professor (tenure-track): University of Nevada Las Vegas, Civil and Environmental Engineering Department. Have taught undergraduate and graduate courses in environmental and civil engineering, including Units Operation, Hazardous and Solid Waste Management, Introductory Engineering Design.

1996-1997 Assistant Professor (non-tenure track): The Pennsylvania State University, Civil and Environmental Engineering Department, University Park.

1995-1996 Environmental Consultant: Buchart Horn GmbH, Germany. Performed characterization study of sludge contained in biological oxidation ponds at Incirlik, Turkey. Investigated possible reclamation options for the ponds, provided cost estimate for possible reclamation options, and wrote final report on the study. 1995-1996.

1991, 1992 Environmental Engineer (Summers only). FMC Gold Company, Gabbs, Nevada, USA. Responsibilities included the preparation of the final closure plan for the facility, including screening of technologies for wastewater treatment, testing of ion exchange resins, and running an activated carbon/alumina adsorption pilot plant to remove selenium and metal-cyanide complexes from an industrial wastewater; selection of available technologies to dispose of mine leachate containing cyanide and toxic metals; Conceptualizing and managing a land application project for the disposal of contaminated mine leachate; and the Preparation of a plan and cost estimate to reclaim and revegetate disturbed mine land. Summers 1991/92.

HONORS AND AWARDS

Full Scholarship for Master's Degree. Montana Power Company, Butte, Montana, USA. 1989 to 1990.
Full Scholarship fro Ph.D. Degree. The Pennsylvania State University and CNPQ.
Student Research Award. Water Pollution Control Association of Pennsylvania, Hershey, PA,1993.

PUBLICATIONS

Batista, Jacimaria R.; Doctoral Dissertation. Removal of Aqueous Selenium by Activated Alumina Adsorption: The Influence of Calcium and Aqueous Silica. The Pennsylvania State University, University Park, PA, 1995.

Batista, Jacimaria R.; M.Sc. Thesis. The Use of Diversion Channels for Effluent Quality Control at the Novo Astro Mine. Montana College of Mineral Science and Technology, Butte, Mt, 1990.

Batista, Jacimaria R. and James C. Young. Removal of Selenium from Gold Heap Leachate by Activated Alumina. 1997. *Minerals and Metallurgical Processing, AIME.*(To be published in the May 1997 issue). (Refereed).

Batista, Jacimaria R. and James C. Young. Removal of Soluble Selenium by Activated Alumina Adsorption. Paper presented at the *65th Annual Conference of the Water Pollution Control Association of Pennsylvania.* Hershey, PA, June 13-16, 1993. (Refereed by Abstract).

Batista, Jacimaria R. and James C. Young. The Influence of Aqueous Silica on the Adsorption of Selenium by Activated Alumina. Paper published at the *Proceedings of the 1994 Annual Conference of the American Water Works Association (AWWA)*, New York, NY. June 19-23, 1994. (Refereed by Abstract).

Batista, Jacimaria R. and James C. Young. Adsorption of Selenium From Gold Heap Leachate by Activated Alumina. Final Report. Environmental Resources Research Institute (ERRI), The Pennsylvania State University, PA 16801, USA. June 1993.

STEVE PRICE, P.E.

Environmental Engineer, Camp Dresser & McKee
Professional Civil Engineer: Arizona, 1990; California, 1991

Education

B.S., Civil Engineering, Iowa State University, 1983
M.S., Civil Engineering (Environmental Emphasis), University of Arizona, 1989

Experience

Mr. Price has 12 years of experience primarily focused on drinking water treatment process evaluations, and facilities design. His professional experience includes a wide range of drinking water issues including regulatory compliance evaluations and treatment facilities engineering. He has been involved with several water quality compliance studies, pilot plant studies, surface water and groundwater process design, and construction/implementation projects.

Design and Construction Projects. Mr. Price has been involved in numerous design and construction projects since 1984. These include designs for several groundwater systems in Arizona and surface water treatment facilities for the Santa Clara Valley Water District, City of San Francisco, City of Benicia, and Contra Costa Water District. Prior to joining CDM, he was involved in the design and construction of several steel and prestressed concrete reservoirs, water system pump stations, and wastewater treatment plants. Currently, Mr. Price is managing a multi-million dollar project to convert the residual disinfectant from chlorine to chloramine for the City of San Francisco, CA.

Compliance and Water Quality Studies. Mr. Price has been involved in numerous studies since joining CDM. He was the project manager for an extensive iron corrosion control pilot study for the Tucson, Arizona Water Department. This highly visible project identified a strategy which would allow Tucson to use Colorado River water without the formation of red water in the distribution system. Mr. Price was involved with multi-million dollar pilot studies with the City of San Francisco and Santa Clara Valley Water District to identify long-term needs for these utilities. The ACWD project was completed jointly with other South Bay Aqueduct water users, the Metropolitan Water District of Southern California, and the University of North Carolina. This project was part of an AWWARF project to evaluate bromate mitigation when using advanced oxidation processes.

Along with involvement in numerous pilot studies, Mr. Price has been the project manager or engineer for many water treatment plant evaluations and compliance studies. Mr. Price completed a comprehensive evaluation of East Bay Municipal Utility District's Upper San Leandro plant. This study provides the ground work for the District to conduct a self assessment as part of the Partnership for Safe Water. Specific improvements were recommended to reliably provide a firm treatment capacity at this facility. Mr. Price has also completed studies for the City of Benicia and Metropolitan Water District of Southern California (MWD). The Benicia study evaluated compliance with the current and anticipated Disinfection By-Product (DBP) Rule and the Surface Water Treatment Rule. The MWD project evaluated the standard design criteria and treatment performance for the washwater reclamation processes (WWRP) at filtration plants totaling over 2,000 mgd. Mr. Price also evaluated the WWRP facility at the Los Angeles Aqueduct Filtration Plant.

R. BRUCE CHALMERS, P.E.

Project Manager/Project Engineer, Camp Dresser & McKee
Professional Engineer: California (1983), Nevada

Education

M.S. - Civil Engineering, California State University, Long Beach, 1994
B.S. - Civil Engineering, University of California, Los Angeles, 1980

Experience

Mr. Chalmers has 18 years of design and managerial experience in the fields of water and wastewater engineering. He has been involved in projects encompassing the planning, design and construction management of water storage and distribution facilities; groundwater remediation; sewage collection systems, sewage lift stations, water booster stations, water and wastewater treatment plants, and water storage reservoirs. He has been responsible for the design and management of numerous water and sewer projects, including the design of two reverse osmosis treatment plants, three VOC treatment plants, an ion exchange treatment plant, and two GAC water treatment systems. Mr. Chalmers has extensive field experience with responsibilities as the resident engineer for the construction of a water treatment plant expansion. Mr. Chalmers has also acted as project manager for the construction management of various reservoirs, pipelines and pump stations.

VOC Water Treatment. Mr. Chalmers was the project manager for two VOC water treatment plants with a total capacity of 6,400 gpm. Packed tower aerators were used to remove VOCs from contaminated groundwater. Work included treatment selection, design, and construction services.

Mr. Chalmers was the task leader for a 5,000-gpm VOC treatment plant at an EPA Superfund site in the San Fernando Valley, California. Conceptual design tasks included treatment evaluation and selection, cost estimates and sensitivity analysis. Additional work included a radon investigation and a GAC regeneration study. The design of the treatment facility, included packed towers (PTAs) for VOC removal, vapor phase GAC off-gas treatment, liquid phase GAC potable water polishing, pump station, construction and O&M cost estimates, GAC usage calculations, and WTP design team coordination. Construction services included major equipment purchasing, subcontractor agreements, shop drawing review, and O&M manuals, in association with CDM Engineers & Constructors.

Mr. Chalmers was the project engineer for a 3.0 mgd granular activated carbon (GAC) water treatment system for the City of Redlands, California. Mr. Chalmers' work included preparation of final plans and specifications, cost estimates, and wellhead piping modifications. He was also responsible for construction management during construction of the site facilities and installation of the GAC contactors.

Mr. Chalmers served as the project engineer for the Monrovia TCE Treatment System Feasibility Report for the San Gabriel Basin Water Quality Authority. The report consisted of an evaluation of packed tower aeration, GAC, and modified air stripping techniques for use by the City of Monrovia to remove TCE contamination for existing wells.

As project engineer for the San Gabriel Basin Water Quality Authority, Mr. Chalmers assisted in the development of an alternative treatment handbook that helps water purveyors in the San Gabriel Basin determine which alternative treatment processes could be used to remove various contaminants from their groundwater. The handbook includes information on potential process technologies, detailed process descriptions, evaluation criteria, and treatment capabilities. The manual was designed to be used in the CERCLA process.

Membrane/Ion Exchange Water Treatment. Mr. Chalmers served as the project engineer for: the 3.2 mgd 17th Street Tustin Desalter reverse osmosis treatment plant for the Orange County Water District and City of Tustin; the 6.0 mgd reverse osmosis treatment plant for the Santa Ana Watershed Project Authority (SAWPA) in Riverside, California; the design of a 3-mgd design/build ion exchange project for the Rubidoux Community Services District near Riverside, California; the project engineer for the Chino Basin Desalter No.1 (West) facilities plan; the Alamitos Barrier Feasibility Study using microfiltration/reverse osmosis to treat tertiary wastewater.

CHARLES J. CRUZ

Environmental Engineer, Camp Dresser & McKee

Education

M.S., Civil Engineering - Environmental Engineering and Science, Stanford University, 1991
B.S., Chemical Engineering - Stanford University, 1985

Experience

Mr. Cruz is a chemical engineer with over six years of experience in chemical and environmental engineering, including process engineering, groundwater remediation, and water treatment. He is experienced in treatment and system design, operation and maintenance (O&M), industrial wastewater management, feasibility and treatability studies, and environmental compliance assessments.

Mr. Cruz designed a 5,000 gallon-per-minute (gpm) groundwater treatment plant for a Superfund site remedy in Southern California. The treatment plant was designed to remove volatile organic contaminants from groundwater by packed tower aeration (PTA) and liquid phase carbon adsorption, with vapor phase carbon adsorption used for abatement of the PTA vapor stream. Responsibilities included process, civil and mechanical design, and preparation of construction drawings.

He conducted startup of a groundwater remediation system for an industrial client in Irvine, California. Duties included treatment system O&M and effluent sampling. Mr. Cruz wrote the O&M manual and prepared monthly reports for the regulatory agency.

He designed a groundwater remediation system for an industrial client in Tustin, California. The remediation system was designed to remove organic and inorganic contaminants by oxidation, clarification, and carbon adsorption. Duties included process design, selection of vendor process equipment, and preparation of plant layout, and piping and instrument (P&IDs) drawings.

Mr. Cruz prepared an operations and maintenance (O&M) manual for a Superfund site remedy in Oklahoma. The site remedy included extraction and treatment of contaminated groundwater and hazardous landfill gases. Responsibilities included preparation of procedures and checklists for pre-startup equipment testing, treatment system operation, equipment maintenance, and routine O&M.

Mr. Cruz conducted startup of a 200-gpm groundwater treatment system which utilized steam stripping and carbon adsorption to remove organic contaminants from groundwater. Responsibilities included computer control system programming, treatment process optimization, and operations support.

Mr. Cruz designed, constructed, and operated five pilot treatment systems to evaluate physiochemical treatment processes including chemical oxidation, steam/air stripping, and carbon adsorption. Duties included coordination of pilot system projects, preparation of O&M manuals, and operator training and supervision.

He provided waste characterization support for closure of six wastewater surface impoundments. Sampled liquids and solids from several depths in each impoundment and coordinated organic and inorganic chemical analysis. Results of the characterization were incorporated into the closure plan for the surface impoundments.

For a U.S. Air Force base in Southern California, Mr. Cruz prepared a workplan for a remedial investigation. The scope of work included installation of one soil boring and four groundwater monitoring wells to further characterize vadose zone and groundwater contamination with trichloroethylene. Duties included preparation of a field sampling plan, a health and safety plan, a quality assurance project plan, and bid specifications.

He also performed field work for a remedial investigation at a U.S. Air Force base in Southern California. The scope of work included installation of seven soil borings and four groundwater monitoring wells to further characterize vadose zone and groundwater contamination with jet fuel. Responsibilities included preparation of sample log sheets and collection of soil and groundwater samples.

PROJECT TITLE: APPLICATION OF BIOREACTOR SYSTEMS TO LOW-CONCENTRATION PERCHLORATE-CONTAMINATED WATER (RFP 2530)
AUGUST 16, 1998 TO AUGUST 15, 2000
1998 AWWA RESEARCH FOUNDATION BUDGET FORM

PROJECT CATEGORIES	PERCENT OF TIME	AWWARF FUNDS	IN-KIND CONTRIBUTION	TOTAL
PERSONNEL				
CATEGORY I				
LOGAN, B. E., PI/PD	16.67%	$20,629	$20,629	$41,258
ZIMMERMAN, K. G., RES. TECH.	25.00%	8,842	8,842	17,684
SUBTOTAL, CATEGORY I		29,471	29,471	58,942
CATEGORY II				
GRADUATE ASST (ACAD YEAR)	50.0%	24,780	0	24,780
GRADUATE ASST (ACAD YEAR)	50.0%	18,464	0	18,464
SUBTOTAL, CATEGORY II		43,244	0	43,244
CATEGORY III				
GRADUATE ASST (SUMMER)	50.0%	8,266	0	8,266
GRADUATE ASST (SUMMER)	50.0%	6,159	0	6,159
SUBTOTAL, CATEGORY III		14,425	0	14,425
SUBTOTAL, DIRECT LABOR		87,140	29,471	116,611
FRINGE BENEFITS (SEE BUDGET NOTES)				
25.10% OF CATEGORY I - PSU		7,397	7,397	14,794
12.36% OF CATEGORY II - PSU		5,345	0	5,345
8.19% OF CATEGORY III - PSU		1,182	0	1,182
SUBTOTAL, FRINGE BENEFITS		13,924	7,397	21,321
TRAVEL - TO REDLANDS, CA AND UNIV OF LAS VEGAS, NV		5,120	0	5,120
MATERIALS AND RENTED EQUIPMENT				
EXP. APPARATUS		6,850	0	6,850
GLASSWARE		2,500	0	2,500
CHEMICALS		2,040	0	2,040
OTHER		3,160	0	3,160
SUBTOTAL, MATERIALS & R. E.		14,550	0	14,550
COMPUTER/PHONE/POSTAGE		2,000	0	2,000
OTHER DIRECT COSTS				
PENN STATE-GRAD ASST TUITION REMISSION		18,662	0	18,662
PENN STATE - DIONEX UNIT		0	30,000	30,000
SUBCONTRACT - CDM		17,000	0	17,000
SUBCONTRACT - UNLV, J. R. BATISTA, CO-INVESTIGATOR		49,962	0	49,962
PUBLICATION		3,060	0	3,060
PHOTOCOPIES		1,020	0	1,020
SUBTOTAL, OTHER DIRECT COSTS		89,704	30,000	119,704
TOTAL DIRECT COSTS		212,438	66,868	279,306
INDIRECT COSTS (SEE BUDGET NOTES)				
37.06% OF MTDC - PSU		62,562	13,663	76,225
IN-KIND CONTRIBUTOR AND AMOUNT				
CDM		XXXXXXXXXXX	3,000	3,000
UNLV		XXXXXXXXXXX	27,985	27,985
CITY OF REDLANDS		XXXXXXXXXXX	10,000	10,000
SUBTOTAL, IN-KIND CONTRIBUTIONS		0	40,985	40,985
TOTAL		$275,000	$121,516	$396,516

PROJECT TITLE: APPLICATION OF BIOREACTOR SYSTEMS TO LOW-CONCENTRATION PERCHLORATE-CONTAMINATED WATER (RFP 2530)
AUGUST 16, 1998 TO AUGUST 15, 1999
1998 AWWA RESEARCH FOUNDATION BUDGET FORM

PROJECT CATEGORIES	PERCENT OF TIME	AWWARF FUNDS	IN-KIND CONTRIBUTION	TOTAL
PERSONNEL				
CATEGORY I				
LOGAN, B. E., PI/PD	16.67%	$10,112	$10,112	$20,224
ZIMMERMAN, K. G., RES. TECH.	25.00%	4,334	4,334	8,668
SUBTOTAL, CATEGORY I		14,446	14,446	28,892
CATEGORY II				
GRADUATE ASST (ACAD YEAR)	50.0%	12,147	0	12,147
GRADUATE ASST (ACAD YEAR)	50.0%	12,147	0	12,147
SUBTOTAL, CATEGORY II		24,294	0	24,294
CATEGORY III				
GRADUATE ASST (SUMMER)	50.0%	4,052	0	4,052
GRADUATE ASST (SUMMER)	50.0%	4,052	0	4,052
SUBTOTAL, CATEGORY III		8,104	0	8,104
SUBTOTAL, DIRECT LABOR		46,844	14,446	61,290
FRINGE BENEFITS (SEE BUDGET NOTES)				
25.10% OF CATEGORY I - PSU		3,626	3,626	7,252
12.36% OF CATEGORY II - PSU		3,003	0	3,003
8.19% OF CATEGORY III - PSU		664	0	664
SUBTOTAL, FRINGE BENEFITS		7,293	3,626	10,919
TRAVEL - TO REDLANDS, CA AND UNIV OF LAS VEGAS, NV		2,000	0	2,000
MATERIALS AND RENTED EQUIPMENT				
EXP. APPARATUS		4,000	0	4,000
GLASSWARE		1,000	0	1,000
CHEMICALS		1,000	0	1,000
OTHER		1,600	0	1,600
SUBTOTAL, MATERIALS & R. E.		7,600	0	7,600
COMPUTER/PHONE/POSTAGE		1,500	0	1,500
OTHER DIRECT COSTS				
PENN STATE-GRAD ASST TUITION REMISSION		10,484	0	10,484
PENN STATE - DIONEX UNIT		0	15,000	15,000
SUBCONTRACT - CDM		7,000	0	7,000
SUBCONTRACT - UNLV, J. R. BATISTA, CO-INVESTIGATOR		35,088	0	35,088
PUBLICATION		1,500	0	1,500
PHOTOCOPIES		500	0	500
SUBTOTAL, OTHER DIRECT COSTS		54,572	15,000	69,572
TOTAL DIRECT COSTS		119,809	33,072	152,881
INDIRECT COSTS (SEE BUDGET NOTES)				
37.06% OF MTDC - PSU		36,777	6,697	43,474
IN-KIND CONTRIBUTOR AND AMOUNT				
CDM		XXXXXXXXXXX	1,000	1,000
UNLV		XXXXXXXXXXX	14,730	14,730
CITY OF REDLANDS		XXXXXXXXXXX	8,000	8,000
SUBTOTAL, IN-KIND CONTRIBUTIONS		0	23,730	23,730
TOTAL		$156,586	$63,499	$220,085

PROJECT TITLE: APPLICATION OF BIOREACTOR SYSTEMS TO LOW-CONCENTRATION PERCHLORATE-CONTAMINATED WATER (RFP 2530)
AUGUST 16, 1999 TO AUGUST 15, 2000
1998 AWWA RESEARCH FOUNDATION BUDGET FORM

PROJECT CATEGORIES	PERCENT OF TIME	AWWARF FUNDS	IN-KIND CONTRIBUTION	TOTAL
PERSONNEL				
CATEGORY I				
LOGAN, B. E., PI/PD	16.67%	$10,517	$10,517	$21,034
ZIMMERMAN, K. G., RES. TECH.	25.00%	4,508	4,508	9,016
SUBTOTAL, CATEGORY I		15,025	15,025	30,050
CATEGORY II				
GRADUATE ASST (ACAD YEAR)	50.0%	12,633	0	12,633
GRADUATE ASST (1 SEMESTER)	50.0%	6,317	0	6,317
SUBTOTAL, CATEGORY II		18,950	0	18,950
CATEGORY III				
GRADUATE ASST (SUMMER)	50.0%	4,214	0	4,214
GRADUATE ASST (1/2 OF SUMMER)	50.0%	2,107	0	2,107
SUBTOTAL, CATEGORY III		6,321	0	6,321
SUBTOTAL, DIRECT LABOR		40,296	15,025	55,321
FRINGE BENEFITS (SEE BUDGET NOTES)				
25.10% OF CATEGORY I - PSU		3,771	3,771	7,542
12.36% OF CATEGORY II - PSU		2,342	0	2,342
8.19% OF CATEGORY III - PSU		518	0	518
SUBTOTAL, FRINGE BENEFITS		6,631	3,771	10,402
TRAVEL - TO REDLANDS, CA AND UNIV OF LAS VEGAS, NV		3,120	0	3,120
MATERIALS AND RENTED EQUIPMENT				
EXP. APPARATUS		2,850	0	2,850
GLASSWARE		1,500	0	1,500
CHEMICALS		1,040	0	1,040
OTHER		1,560	0	1,560
SUBTOTAL, MATERIALS & R. E.		6,950	0	6,950
COMPUTER/PHONE/POSTAGE		500	0	500
OTHER DIRECT COSTS				
PENN STATE-GRAD ASST TUITION REMISSION		8,178	0	8,178
PENN STATE - DIONEX UNIT		0	15,000	15,000
SUBCONTRACT - CDM		10,000	0	10,000
SUBCONTRACT - UNLV, J. R. BATISTA, CO-INVESTIGATOR		14,874	0	14,874
PUBLICATION		1,560	0	1,560
PHOTOCOPIES		520	0	520
SUBTOTAL, OTHER DIRECT COSTS		35,132	15,000	50,132
TOTAL DIRECT COSTS		92,629	33,796	126,425
INDIRECT COSTS (SEE BUDGET NOTES)				
37.06% OF MTDC - PSU		25,785	6,966	32,751
IN-KIND CONTRIBUTOR AND AMOUNT				
CDM		XXXXXXXXXXX	2,000	2,000
UNLV		XXXXXXXXXXX	13,255	13,255
CITY OF REDLANDS		XXXXXXXXXXX	2,000	2,000
SUBTOTAL, IN-KIND CONTRIBUTIONS		0	17,255	17,255
TOTAL		$118,414	$58,017	$176,431

BUDGET NOTES

1. SALARY COSTS ARE BASED ON CURRENT SALARY RATES (FISCAL 1997-98) ESCALATED 4% BEGINNING JULY 1 OF EACH SUBSEQUENT YEAR. UNIVERSITY POLICY HAS BEEN TO AWARD SALARY INCREASES ON THE BASIS OF MERIT ONLY. THE ESTIMATED AVERAGE MERIT INCREASE IN SALARIES IS 4%.

2. FRINGE BENEFIT RATES ARE NEGOTIATED AND APPROVED BY THE OFFICE OF NAVAL RESEARCH, PENN STATE'S COGNIZANT FEDERAL AGENCY. FIXED RATES FOR JULY 1, 1997 AND FORWARD ARE 25.10% FOR CATEGORY I, 12.36% FOR CATEGORY II, AND 8.19% FOR CATEGORY III.

   CATEGORY I - ALL SALARIES EXCEPT THOSE INCLUDED IN CATEGORIES II AND III.
   CATEGORY II - GRADUATE ASSISTANTS.
   CATEGORY III - WAGES AND FIXED TERM II.

3. ALL TRAVEL WILL BE IN ACCORDANCE WITH UNIVERSITY TRAVEL REGULATIONS. TRAVEL ESTIMATES ARE BASED ON COSTS THAT WERE INCURRED ON PREVIOUS PROJECTS OF A SIMILAR NATURE FOR FEDERAL AND STATE AGENCIES.

4. TUITION IS CALCULATED USING THE PREDETERMINED RATES OF $2,520/SEMESTER AND $1,260/SUMMER TERM. AN ESCALATION FACTOR OF 4% IS APPLIED IN THE FALL SEMESTER OF EACH SUBSEQUENT YEAR.

5. INDIRECT COSTS RATES ARE NEGOTIATED AND APPROVED BY THE OFFICE OF NAVAL RESEARCH, PENN STATE'S COGNIZANT FEDERAL AGENCY. THE FIXED RATE FOR JULY 1, 1997 AND FORWARD IS 37.06% (ON CAMPUS) OF MTDC. THE ADDRESS OF THE COGNIZANT FEDERAL AGENCY IS: GERALD SMITH, OFFICE OF NAVAL RESEARCH, CHICAGO REGIONAL OFFICE, FEDERAL BUILDING, ROOM 208, 536 SOUTH CLARK STREET, CHICAGO, IL, 60605-1588. PHONE (312) 886-5423 EXT. 229 FAX (312) 353-6089

In-kind Support Worksheet for Participating Utilities And Other Participating Organizations

Name of Organization	Name of Contact	Letter of Support (yes/no)	Amount Specified in Letter (U.S.$)
Camp, Dresser, and McKee, Inc.	Frederick H. Elwell	Yes	$ 3,000
Univ. of Nevada, Las Vegas	Jacimaria R. Batista	Yes	27,985
City of Redlands, CA	Michael L. Huffstutler	Yes	10,000
Penn State University	Archie J. McDonnell	Yes	30,000
Penn State University	Archie J. McDonnell	Yes	50,531
		*Total In-kind ($)	+ 121,516

*Please note: The scope of work must be based only on this amount plus the AWWARF funding any in-kind contributions provided by the organization(s) submitting and signing this proposal.

+ Insert this figure in the box numbered "4" on the Unsolicited Proposal Budget Form.

ATTACHMENTS

- Support Letters:
  - City of Redlands
  - Camp, Dresser, and McKee
  - Dr. Jaci Batista, University of Nevada, Las Vegas
  - Dr. Arche J. McDonnell, The Pennsylvania State University
  - Dr. Archie J. McDonnell, The Pennsylvania State University
- Patent Application No. 1887

City of Redlands

April 27, 1998

Dr. Bruce Logan, Kappe Professor
Department of Civil and Environmental Engineering
212 Sackett Building
The Pennsylvania state University
University Park, PA 16802

AWWARF Proposal regarding Removal of Perchlorate (RFP2530).

The City of Redlands would be pleased to collaborate in the above referenced proposal. Redlands has been using granulated activated carbon (GAC) at a full scale 8.6 MGD facility that is designed to remove organic compounds (TCE & DBCP) from well water. Water from this particular facility contains the afore mentioned constituents, some nitrates, and perchlorate at levels up to 138 μg/l. The system is designed to provide complete removal of the volatile organic compounds (VOCs) and has worked well in that area. However, during operation, we have found that there is also some perchlorate removal for a short period of time after total replacement with virgin or offsite regenerated carbon. The short term removal is limited and experience has shown that after a short time there can be process effluent levels of perchlorate that are higher than the levels in the influent.

Redlands is willing to provide some "in kind" participation for this research project. Redlands in kind support would include pumping a perchlorate affected well (No. 31A) to collect a representative sample. The sample would be sent to Penn state for use in a bench scale treatment system.. Redlands would also provide operator overview of the well pump. Redlands could conduct some analysis on the water produced (no perchlorate analysis), and is willing to provide water and media samples to your team from our existing full scale GAC units. It is anticipated that if the project were to continue for a period of four to six months,, and several samples are required, the total in kind value of the activity that Redlands could provide would exceed $10,000.

The City of Redlands looks forward to further consideration of the proposed project, and believes that a coordinated effort between ourselves and your team could prove beneficial to all concerned.

If you have any questions regarding this matter, please feel free to contact me at the address indicated below or at (9090-798-7698.

Michael L. Huffstutler

Michael L. Huffstutler, Chief of Water Resources

CDM Camp Dresser & McKee Inc.

consulting
engineering
construction
operations

2301 Maitland Center Parkway, Suite 300
Maitland, Florida 32751
Tel: 407 660-2552 Fax: 407 875-1161

April 28, 1998

Dr. Bruce E. Logan
Kappe Professor
Department of Civil and Environmental Engineering
212 Sackett Building
The Pennsylvania State University
University Park, PA 16802

Subject: AWWARF Proposal No. 2530
Application of Bioreator Systems
Letter of Commitment

Dear Dr. Logan:

Camp Dresser & McKee Inc. (CDM) is pleased to collaborate for AWWARF Project No. 2530. CDM has extensive experience with groundwater remediation projects related to drinking water systems for our clients.

CDM will provide process engineering for this project to develop a conceptual design for the processes found to effectively remove perchlorate from groundwater. Process schematics, cost curves, and design and operational issues will be addressed through our work. CDM will also be available to consult on design and operational issues throughout Phase 1 of this work.

For this project, CDM's total budget will be $20,000. Our in-kind contribution will be $3,000, with the remaining $17,000 provided through the AWWARF contract.

Please feel free to contact Mr. Steve Price at (925) 933-2900 with any questions.

Very truly yours,
CAMP DRESSER & McKEE

Frederick H. Elwell

Frederick H. Elwell
Senior Vice President

gd1150

UNLV
UNIVERSITY OF NEVADA LAS VEGAS

April 25, 1998

Letter of Support

This letter is written as a strong support to the proposed research " Application of Bioreactor Systems to Low-Concentration Perchlorate-Contaminated Water -RFP 2530" by Dr. Bruce Logan. I am very interested in this collaborative effort, given the importance of perchlorate removal technologies to the Las Vegas community. Since the perchlorate problem in Southern Nevada became public, scientists from all over the US have been investigating the interactions of perchlorate with the environment as a means of gaining insight into economical remedial technologies to remove perchlorate from waters. The reason for the strong interest in this research area is that not only California and Nevada, but also Air Force Bases located in several other states have perchlorate-contaminated waters that require remediation. In Nevada, the responsible water authorities and involved industries, namely Kerr-McGee and Pacific Engineering & Production Co. (PEPCON), are looking for effective remedial measures to treat the contaminated waters. One of the wells located in the vicinity of a perchlorate manufacturing plant has a perchlorate concentration of 3700 parts per million (ppm) leading to the possibility of heavy contamination of groundwater near the plant. The plant is upstream of the Las Vegas Wash, a stream that feeds into Lake Mead, *the major drinking water source to the City of Las Vegas*.

The Department of Environmental Engineering at the University of Nevada Las Vegas (UNLV) has a very good relationship with the water authorities and industries in the Valley. We have easy access to research samples and laboratory facilities to support the proposed research activities. Our participation in the first 1.5 years of research includes testing the membrane biofilm reactor, providing perchlorate-contaminated samples from the Las Vegas Valley for the research, and assisting filing reports(3/years). UNLV will provide $14,730 in-kind contribution for the first year of the project and $13,255 for the second year of the project. The in-kind contribution include faculty research time and sample analysis.

I believe the results of this research would significantly contribute to the decisions that need to be made about decreasing the uncertainty and the risk associated with consuming pechlorate-containing water and reducing perchlorate contamination in several locations in the United States. I strongly support this research and I am committed to assisting the proposed activities to completion.

Jacimaria Ramos Batista

Jacimaria R. Batista, Ph.D
Assistant Professor of Environmental Engineering

Department of Civil and Environmental Engineering
4505 Maryland Parkway • Box 454015• Las Vegas, Nevada 89154-4015
(702) 895-3701 • FAX (702) 895-3936

PENNSTATE

Dept. of Civil and Environmental Engineering
212 Sackett Building
The Pennsylvania State University
University Park, PA 16802

Dept: 814-865-8391
Office: 814-863-7908
Fax: 814-863-7304
Email: blogan@psu.edu

April 22, 1998

Memorandum

TO: John Mason, Associate Dean, College of Engineering
Paul Jovanis, Head, Department of Civil and Environmental Engineering
Archie McDonnell, Director ERRI

From: Bruce Logan, Kappe Professor of Environmental Engineering

Subject: Equipment Support for AWWARF Proposal

By way of this Memorandum, I am requesting confirmation of support for an AWWARF proposal "Application of Bioreactor Systems to Low-Concentration Perchlorate Contaminated Water, FRP 2530". The funding would be split among the Department of Civil and Environmental Engineering, the College of Engineering, and ERRI, as indicated below, for a Dionex 500 Ion Chromatograph. Such support is contingent upon funding from AWWARF.

Dept. Civil and Environmental Engineering: 1998-1999: $5,000
1999-2000: $5,000

Paul P. Jovanis 4/28/98
Paul Jovanis Date

College of Engineering: 1998-1999: $5,000
1999-2000: $5,000

John Mason 4/28/98
John Mason Date

ERRI: 1998-1999: $5,000
1999-2000: $5,000

Archie McDonnell 4/28/98
Archie McDonnell Date

PENNSTATE

1855

Environmental Resources Research Institute

The Pennsylvania State University
Land and Water Research Building
University Park, PA 16802-4900

(814) 863-0291
Fax: (814) 865-3378

April 30, 1998

Traci L. Case
AWWA Research Foundation
666 West Quincy Avenue
Denver, CO 80235

Dear Ms. Case:

The Environmental Resources Research Institute will provide an in-kind contribution of $50,531 for the proposed project (RFP 2530). This will consist of salaries of $29,471, fringe benefits of $7,397, and indirect costs of $13, 663.

Sincerely,

Archie J. McDonnell

Archie J. McDonnell
Director, ERRI

PENNSTATE

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INTEROFFICE CORRESPONDENCE

Intellectual Property Office
113 Technology Center
865-6277

Date: April 14, 1998

From: B.A. Romano

To: B.E. Logan

Subject: "Process for Treating Perchlorate-Contaminated Drinking Water"
By B.E. Logan
PSU Invention Disclosure No. 1887

Enclosed for your records is a copy of the Provisional Application that was filed with the U.S. Patent and Trademark Office on April 3, 1998. We will keep you informed of future activities with respect to the protection of this technology.

Thank you for your assistance with this matter.

BAR/clw

Enclosure

cc: R.J. Huss
K. Kresovich

Invention: Process for treating Perchlorate-contaminated drinking water

Inventor: Bruce E. Logan
Date: 11-February-1998

Abstract: Perchlorate-contaminated water is treated in an anaerobic biofilm reactor under highly reduced conditions. A packed bed reactor is used to grow perchlorate-respiring bacteria and through their respiration perchlorate is removed to the ppb range or lower. The reactor is run either as a four-phase system (gas, water, bacteria, and solid support) where bacterial growth is supported through the oxidation of hydrogen gas provided in an in an oxygen-free atmosphere, or as a three-phase system (water, bacteria, and solid support) where bacteria are grown on soluble substrates in water.

Background

The contamination of waters with perchlorate is potentially a national concern with few known methods of economically treating the water. The California Department of Health Services (CDSH) sampled 232 ground water wells in California and found perchlorate in 69 wells (30%), and found 20 wells (9% of all wells sampled) with contamination of >18 ppb, the State's provisional action level. High doses of the chemical interfere with the operation of the thyroid, and at lower doses perchlorate interferes with the absorption of iodine by the thyroid and is therefore a serious human health concern when present in drinking water (AWWARF 1997).

It was the consensus of a team of experts that met at a special workshop on perchlorate that "at this time there is no proven removal process available at the low concentrations being found in drinking water" (AWWARF, 1997). Typical water treatment technologies such as ion exchange, air stripping, carbon adsorption and advanced oxidation, have little effect on perchlorate which is extemely stable in water. Merely lowering the Eh of the water to the range below -200 mV does not produce perchlorate reduction (Bliven 1996).

Patent Claims

It is well known that several strains of bacteria are able to respire using perchlorate and chlorate. In order to remove perchlorate from large volumes of water, the following process can be used.

The perchlorate biofilm reactor shall be a anaerobic biofilm packed bed reactor used specifically to grow perchlorate-respiring bacteria and treat water (surface water and ground water) to remove perchlorate to the ppb range or lower. This reactor shall have the following properties:

1. It will be inoculated with microbial cultures (either pure cultures or mixed cultures) in order to produce a bacterial biofilm on the reactor packing (sand, stones, plastic, or activated carbon are typical support media).

2. The reactor can be run in either unsaturated mode (gas phase present) and/or saturated-mode (no gas phase).

3. In unsaturated mode, a hydrogen gas (either fed from a containerized source or created on site electrolytically or by another means) is added into the reactor gas phase, but oxygen must be excluded from the gas phase. Water flows down through the reactor, so that the microbes growing on the column packing use the hydrogen gas as an electron donor (food source) and use the perchlorate as an electron acceptor (for respiration) accomplishing perchlorate removal.

4. If the reactor is operated in the saturated mode operation, the electron donor (such as hydrogen or other soluble substrates such as acetate, ethanol and methanol) is added directly to the water prior to entering the reactor or provided by a permeable membrane.

5. The reactor may consist of several sections (i.e. there may be several reactors in series) each optimized for a different strategy, but linked in order to optimize the removal of the perchlorate. The first reactor may be optimized for the removal of oxygen from the water because anoxic conditions are necessary to promote perchlorate reduction. A reactor may be added following the perchlorate biofilm reactor to remove any remaining electron acceptor in this post treatment process (for example an anaerobic reactor where carbon dioxide serves as an electron acceptor, or a separate aerobic reactor where oxygen can be used as an electron acceptor).

6. The biofilm in the anaerobic biofilm reactor can be regenerated by temporarily halting the flow of contaminated water through the reactor, and recycling water containing relatively high concentrations of electron donor and electron acceptor (such as chlorate at mg/L levels) to that bacteria may grow and for a thick biofilm. The reactor can then be placed back in service by rinsing with clean water. Contaminated water can be held for subsequent treatment or treated in the reactor through continuous recycle.

7. The reactor may be designed for backwashing, in order to redistribute bacteria that preferentially will grow near the column effluent to the whole column, and in order to dislodge old biofilm or other material that may accumulate on the media packing.

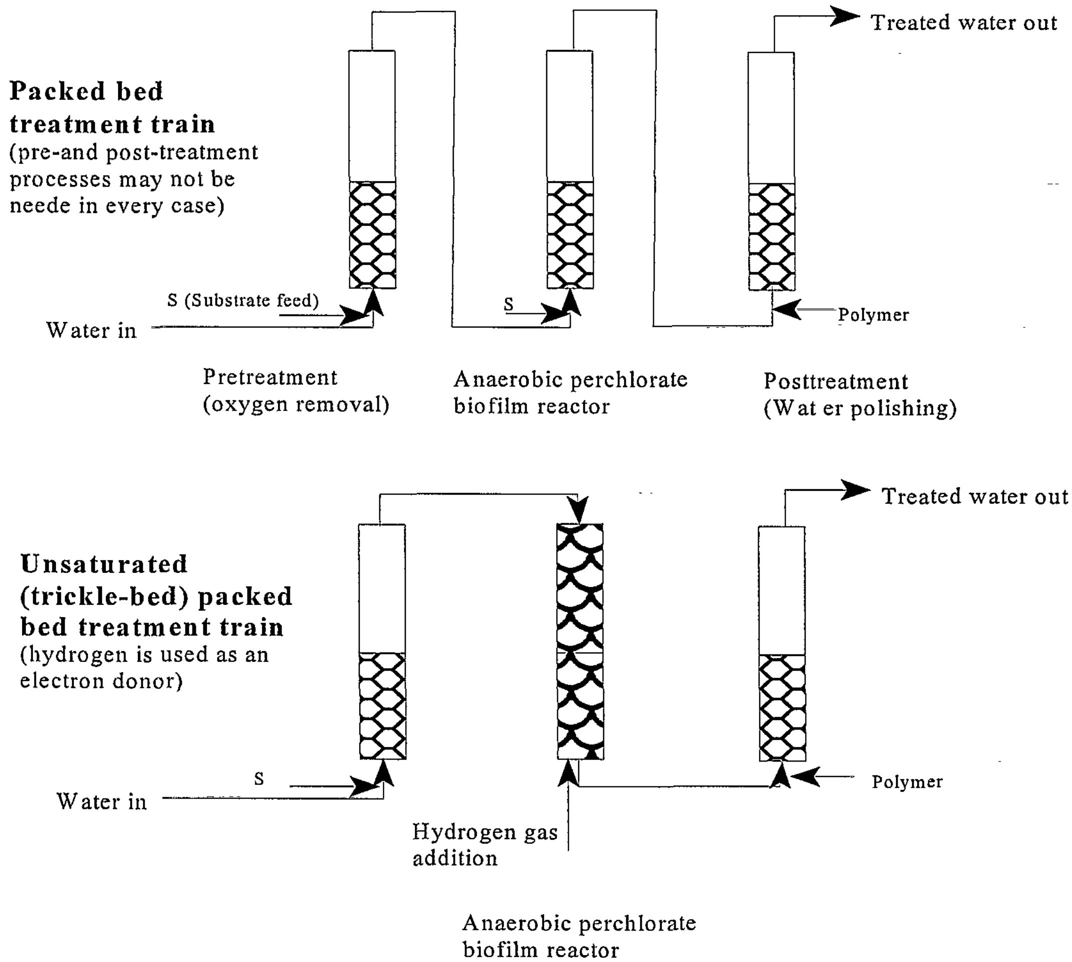

Figure 1. (A) Process train for treating perchlorate contaminated water. The pre-and post-treatment trains may not be needed in all cases. Pretreatment functions to consume all oxygen for the anaerobic perchlorate biofilm reactor, while posttreatment is provided to remove any sloughed biofilm and to provide for biological polishing of any remaining growth substrate (S) in the water sample. (B) Here, the biofilm reactor is shown to contain a gas phase of hydrogen that serves as the electron donor in the biological process.